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Clarke

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[54] **DUAL COMPRESSION AND DUAL EXPANSION INTERNAL COMBUSTION ENGINE AND METHOD THEREFOR**

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[21] Appl. No.: **361,272**

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### Related U.S. Application Data

[62] Division of Ser. No. 119,106, Apr. 1, 1991.

[51] Int. Cl.<sup>6</sup> ..... **F02B 59/00**

[52] U.S. Cl. .... **123/42; 123/51 AA; 123/50 B**

[58] Field of Search ..... 123/46 R, 48 B, 123/78 B, 61 R, 42, 51 AA, 51 R, 51 B, 51 A, 62, 63, 193.6, 509, 197.1, 508, 55.2, 50 R, 50 A, 50 B

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Attorney, Agent, or Firm—Kenneth A. Rhoads

102 Claims, 11 Drawing Sheets

### [57] ABSTRACT

An apparatus and method is provided for a dual compression and dual expansion internal combustion engine (8) that is compact, efficient, and has low combustion noise and emissions. The subject engine (8) includes a low pressure piston assembly (56) reciprocally disposed in an operating chamber (22) defined in a housing (10). A pair of opposed high pressure piston assemblies (58) and (60) are directly mounted on a pair of geared together, counter rotating, crankshafts (52) and (54) and reciprocally disposed in bores (178) and (186) of the low pressure piston assembly (56). The disposition of the second and third piston assemblies (58) and (60) within their respective bores (178) and (186) defines a combustion chamber (254). An intake chamber (144) for compression of inducted air and an exhaust chamber (146) for expansion of exhaust gas are defined in the operating chamber (22) between the low pressure piston assembly (56) and the housing (10). Air moves from the intake chamber (144) to the exhaust chamber (146), but in the process the air is compressed, mixed with fuel, and combusted. The resulting gas is expanded in the combustion space (254) between the high pressure piston assemblies (56) and (60). A complete cycle from start of air entry into the intake chamber (144) to the exit of the exhaust gas of the same charge from the exhaust chamber (146) takes approximately 900 degrees of rotation of the crankshafts (52) and (54) during which the intake chamber (254), the combustion chamber (254), and the exhaust chamber (146) each undergoes five "strokes".

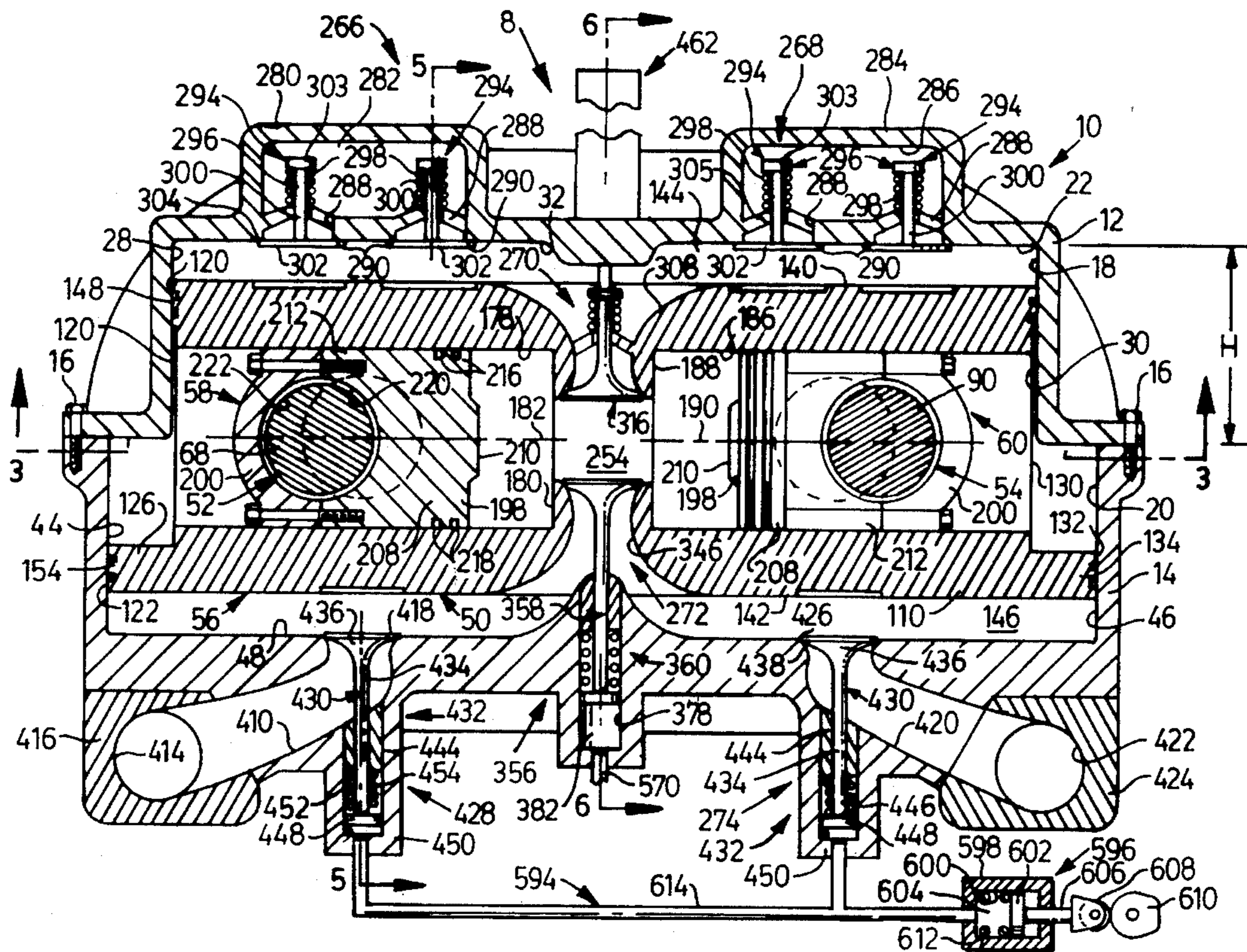
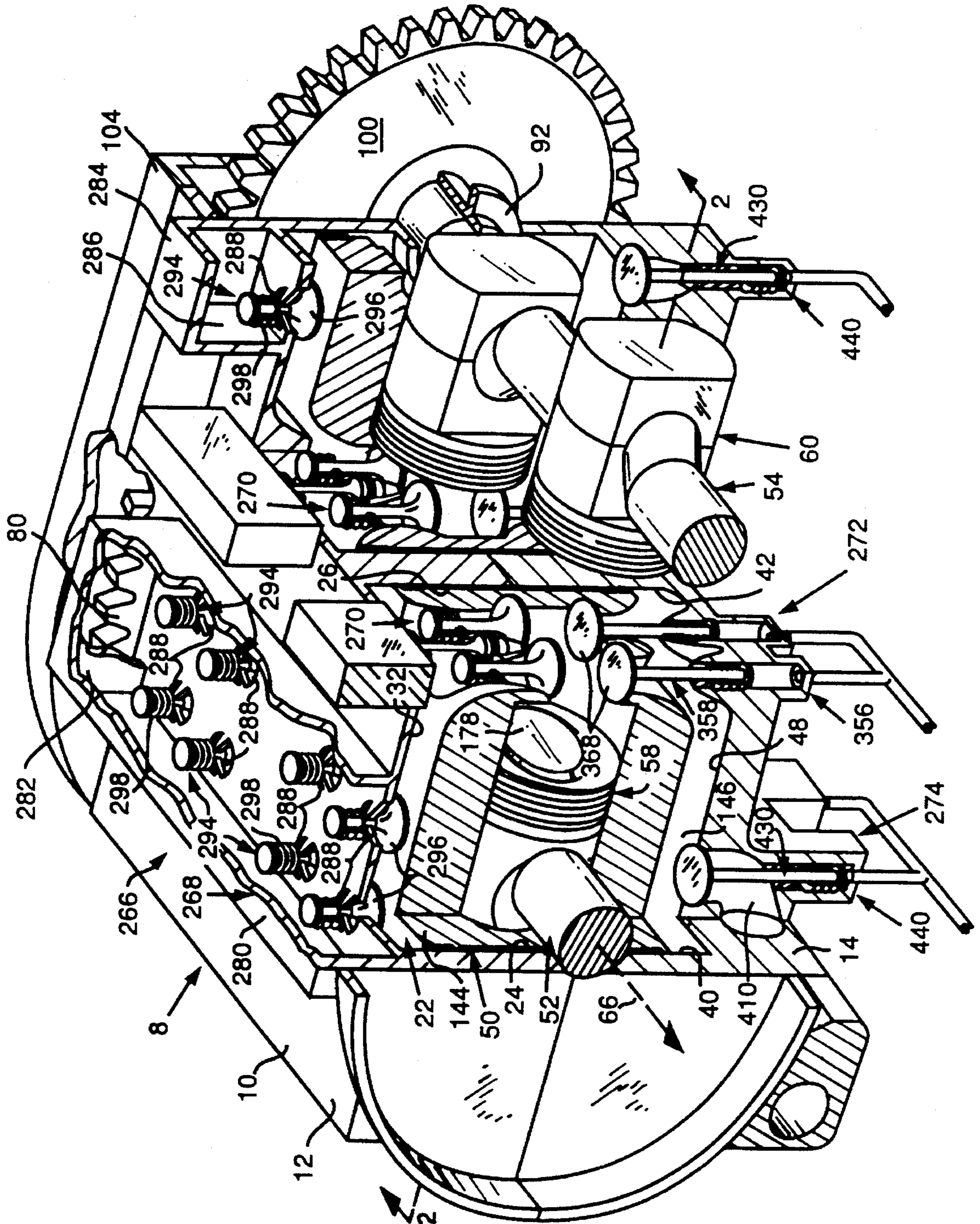
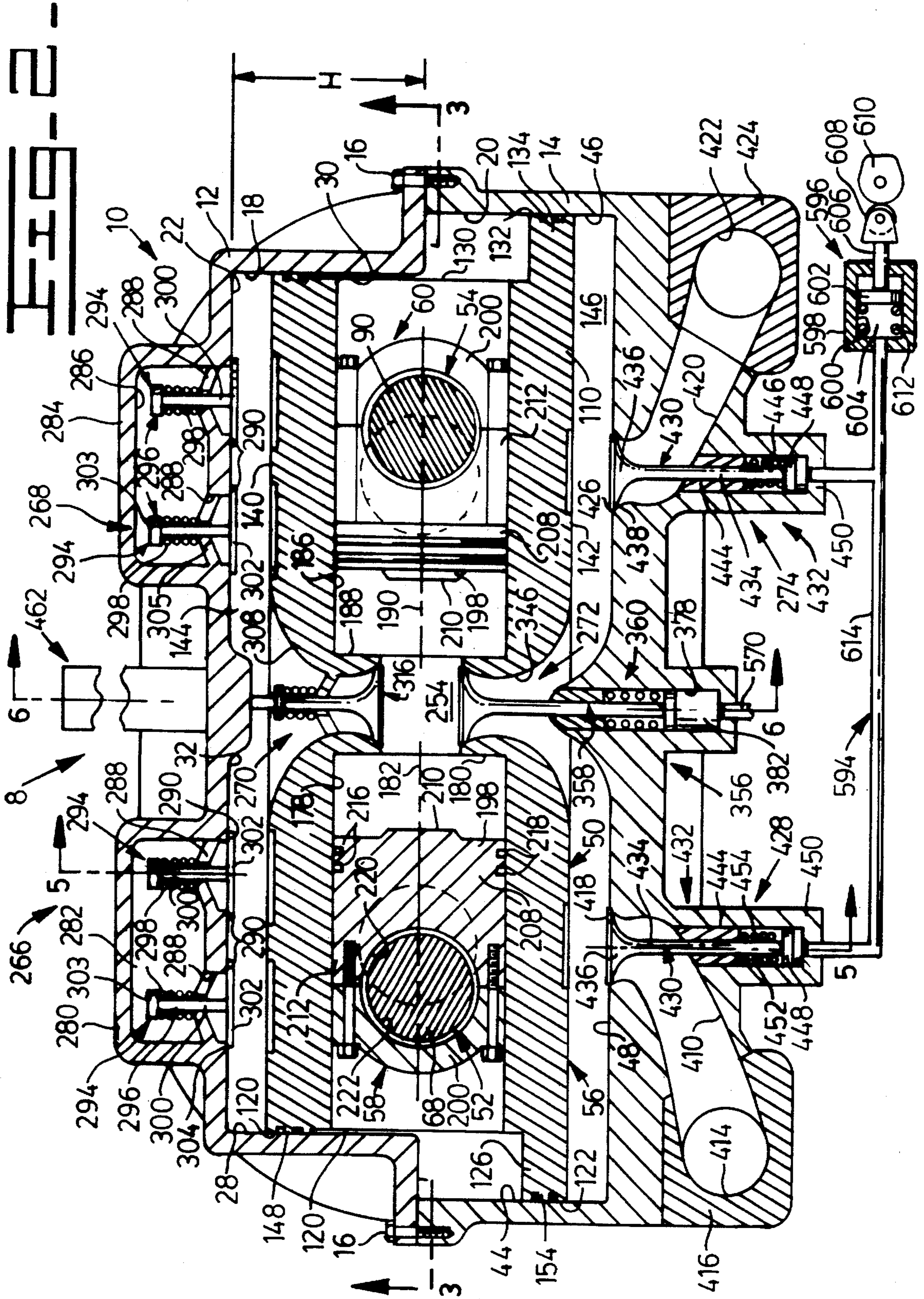




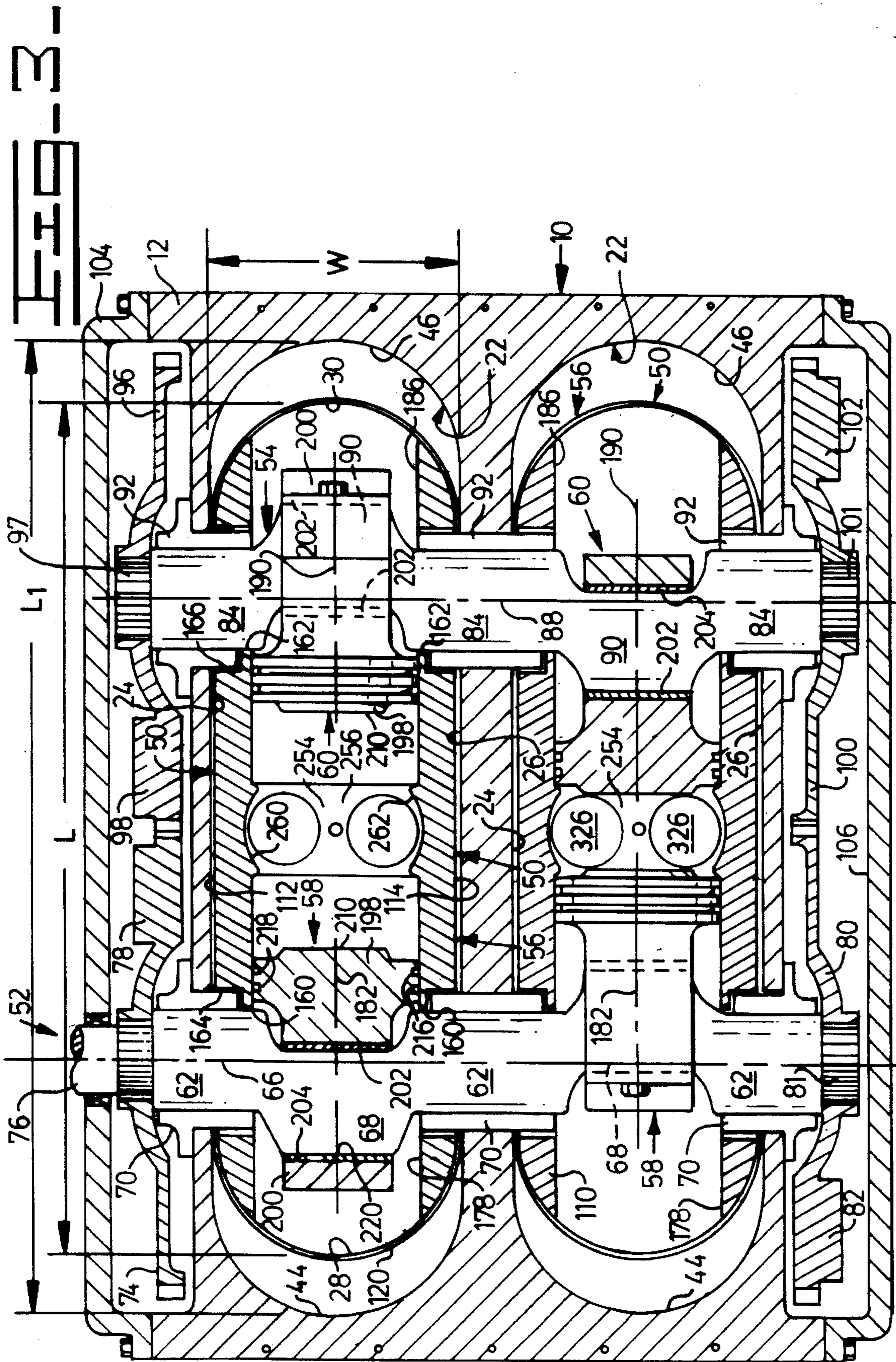
FIG. 1











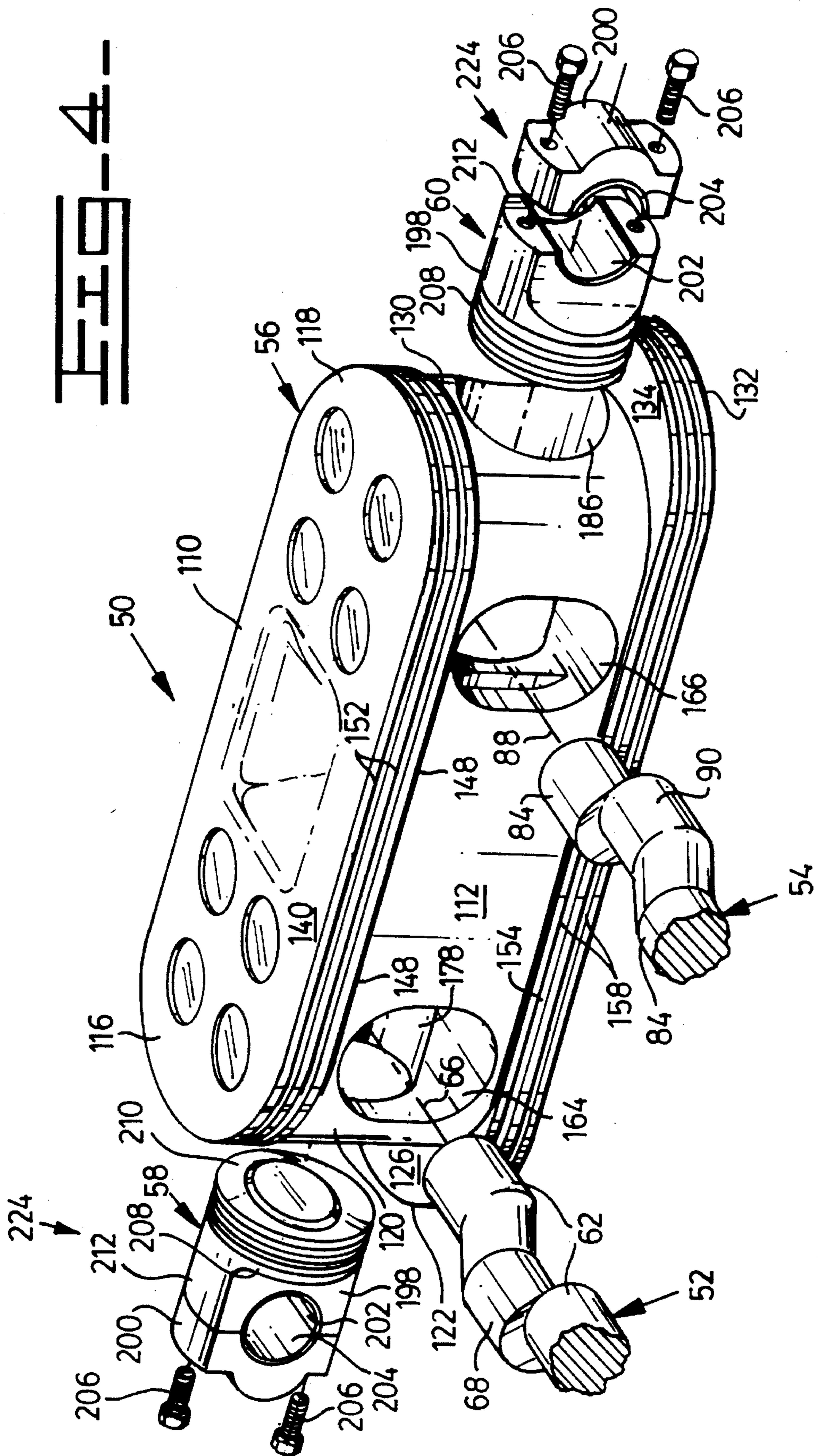




FIG. 5

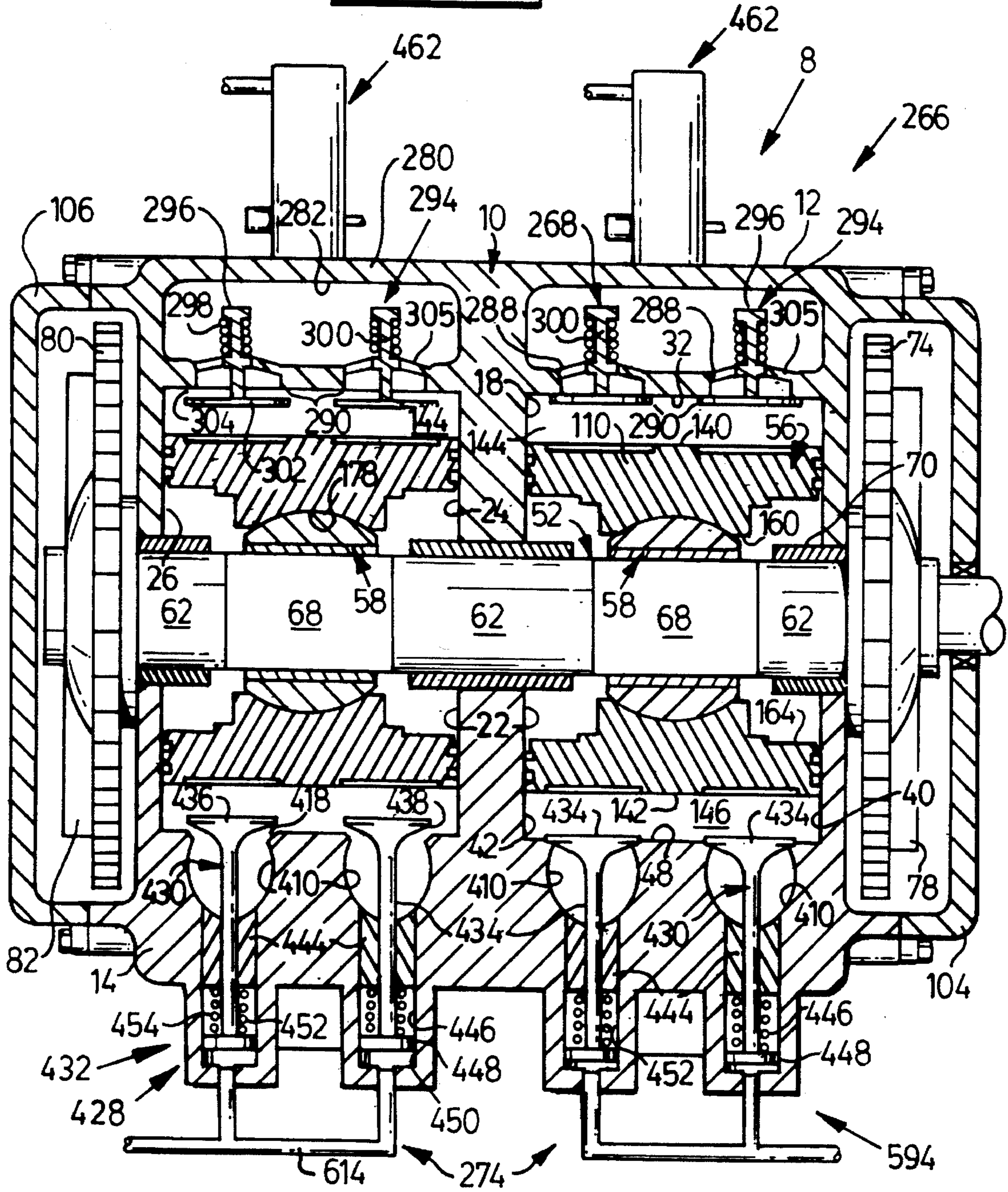


FIG. 6.

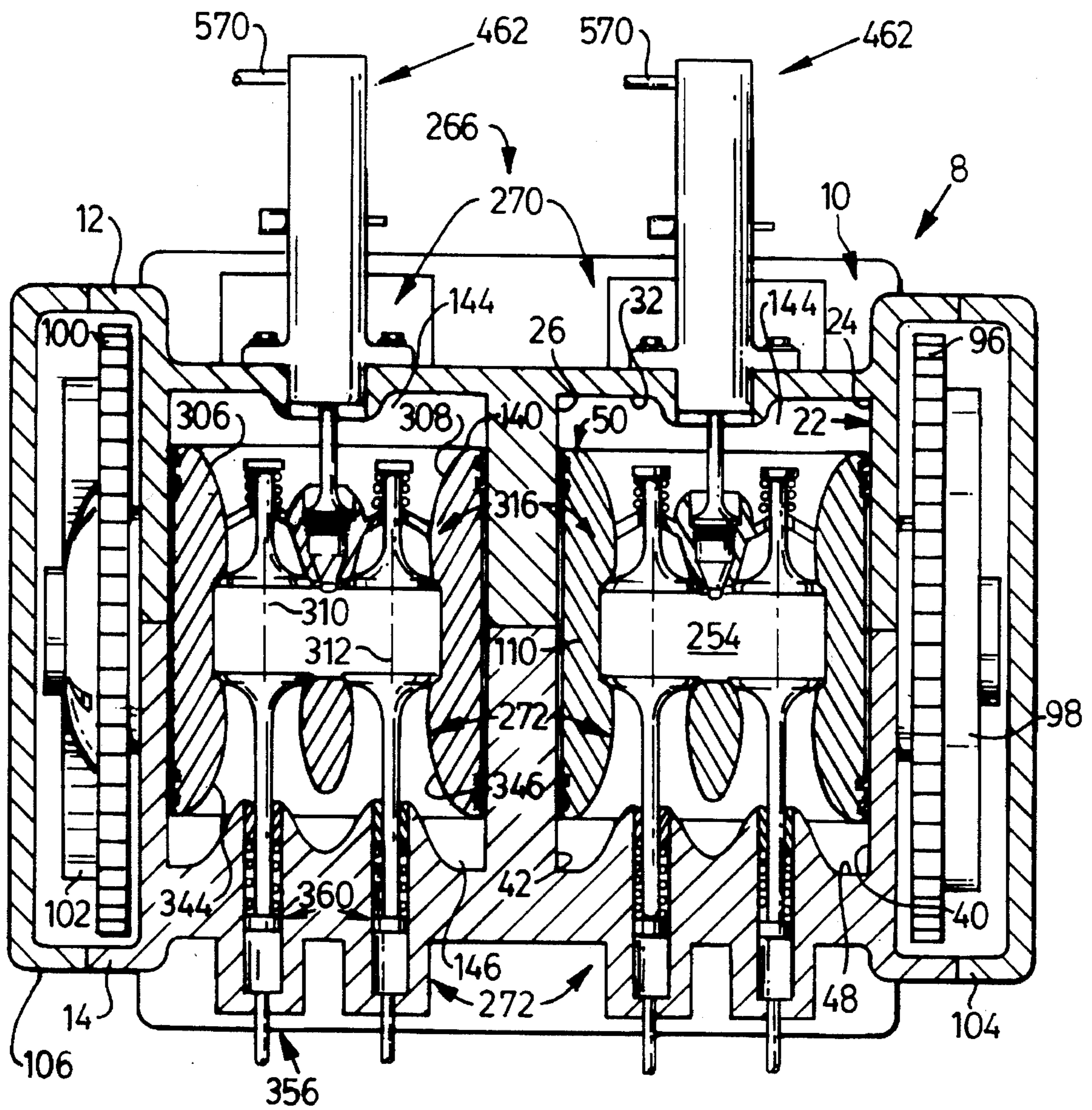
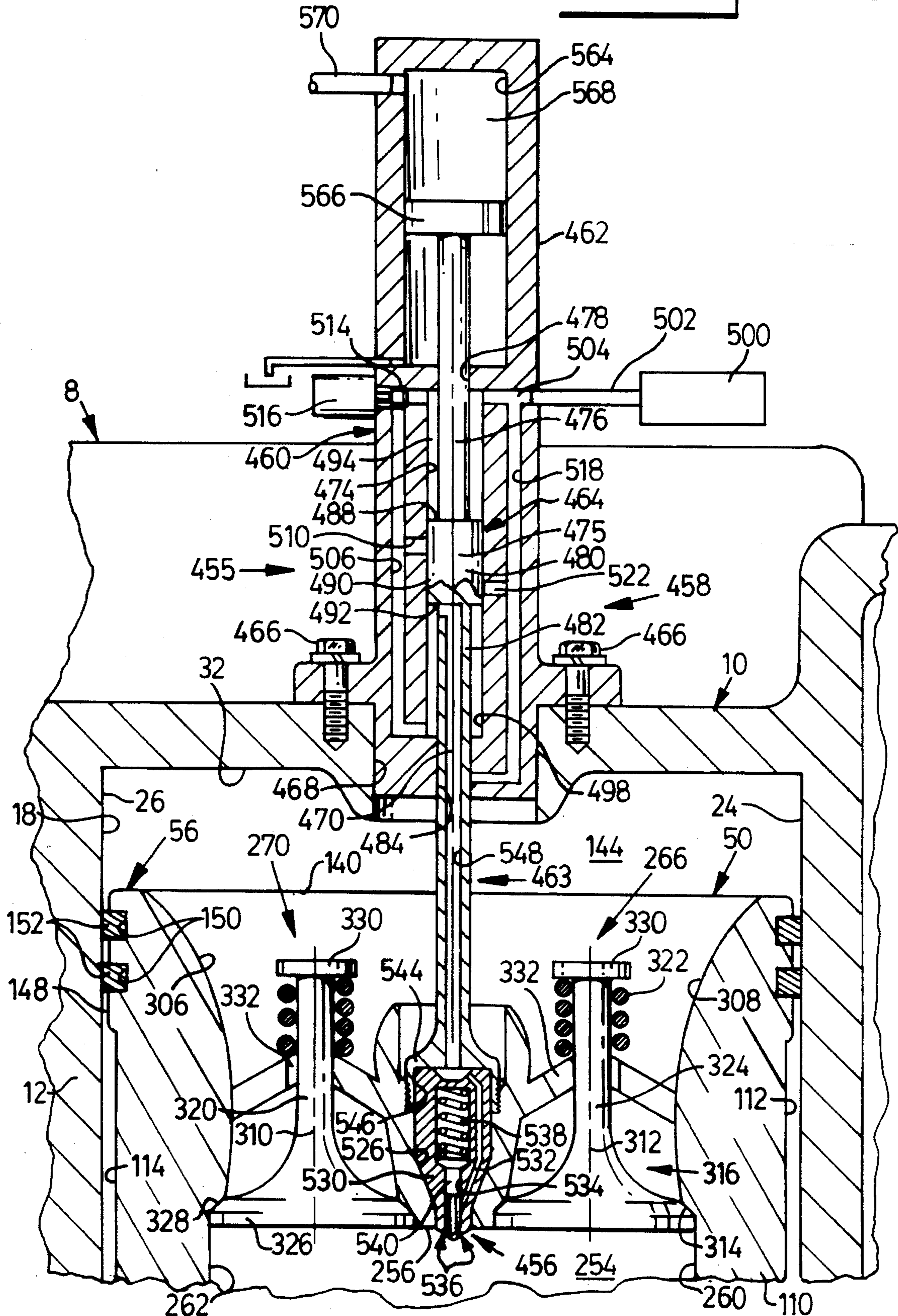








FIG. 8



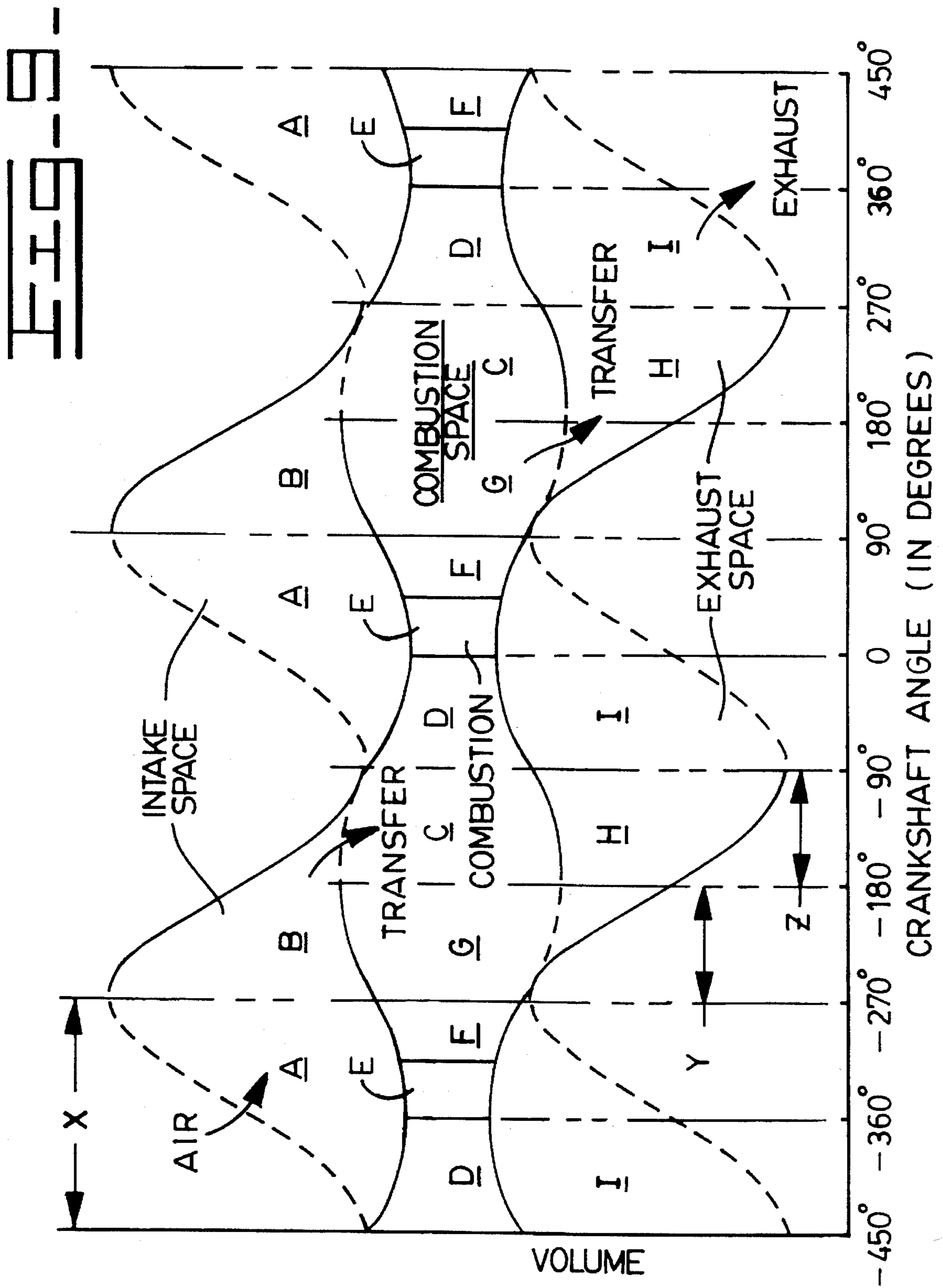




FIG-10a-

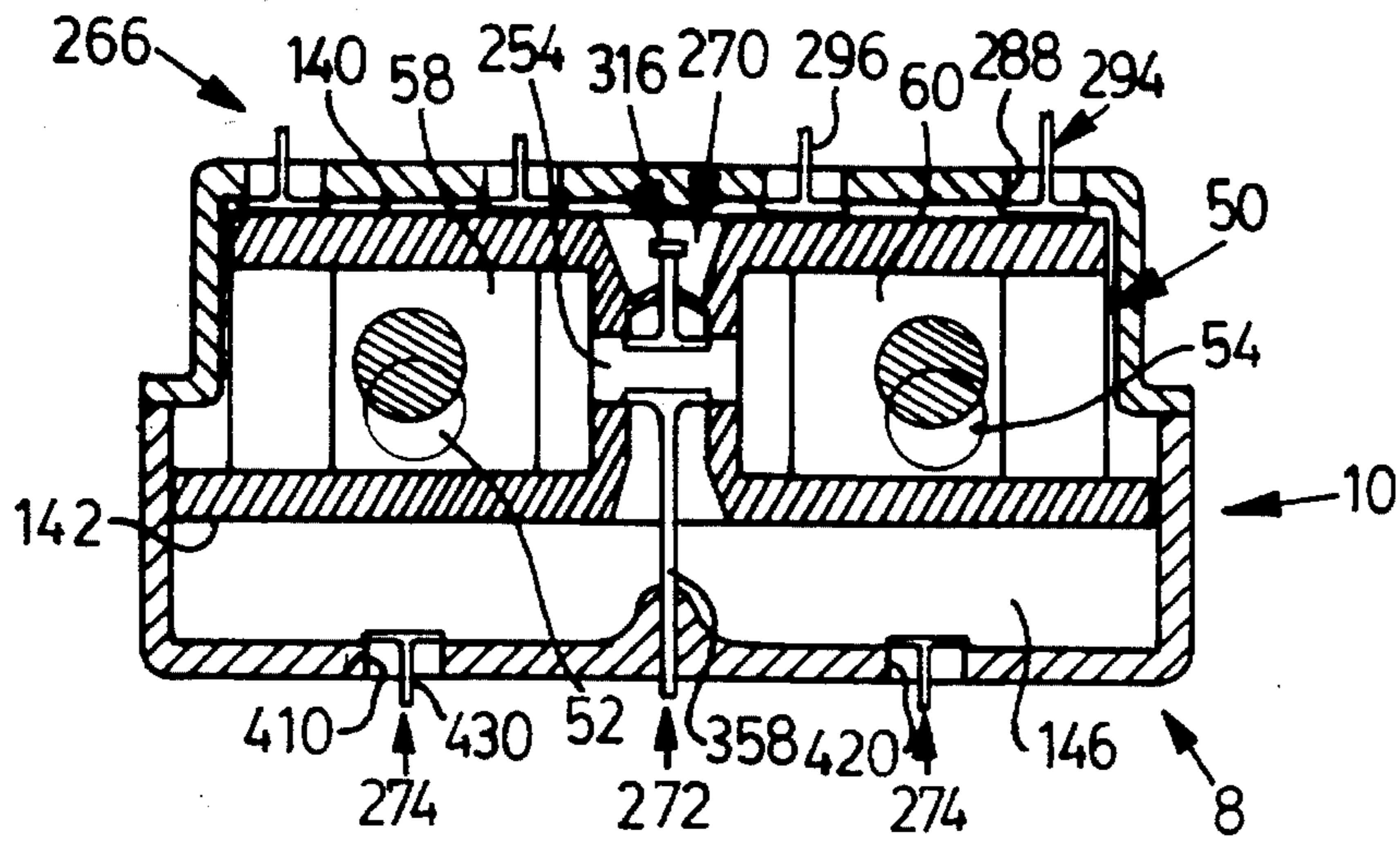


FIG-10b-

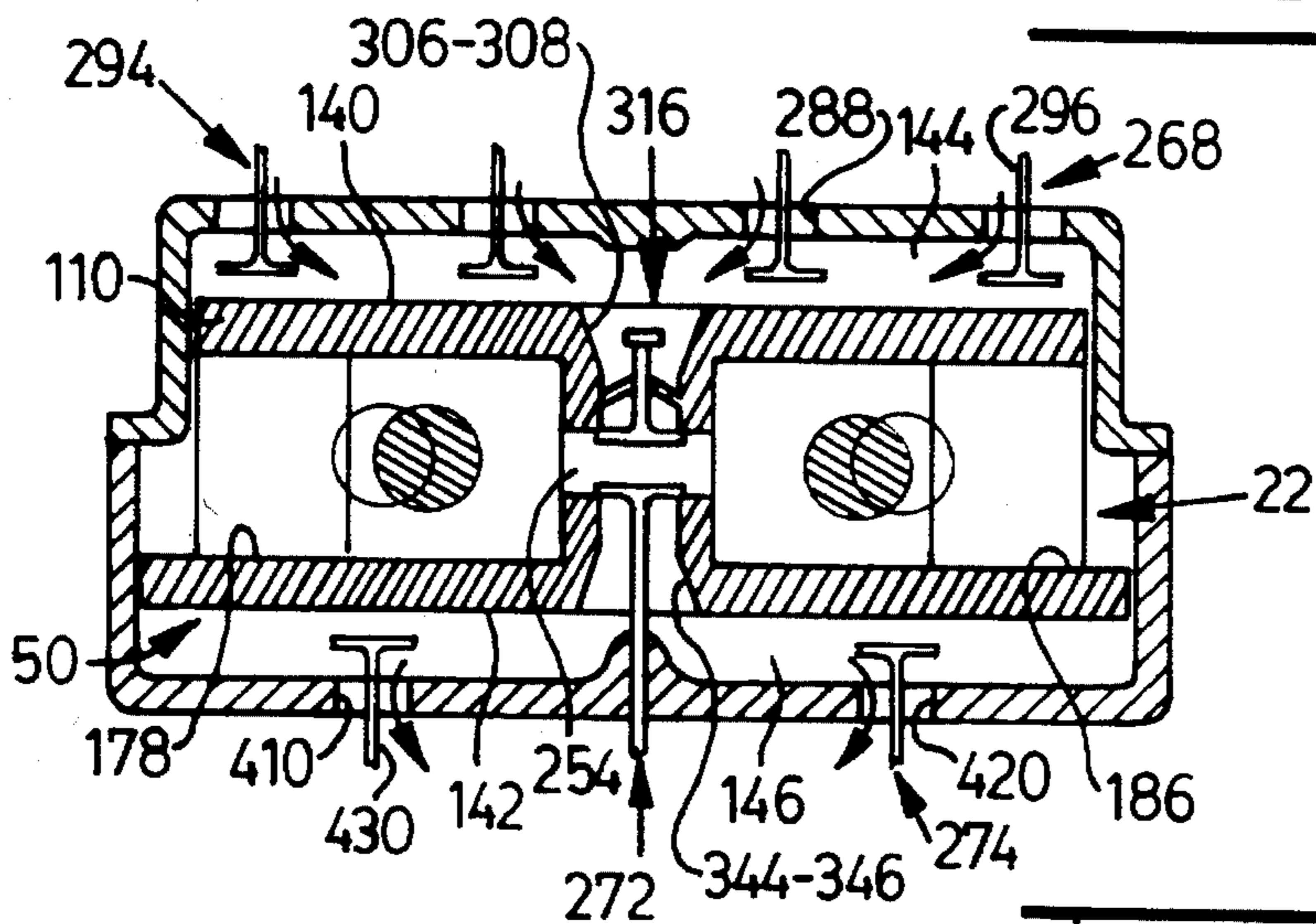


FIG-10c-

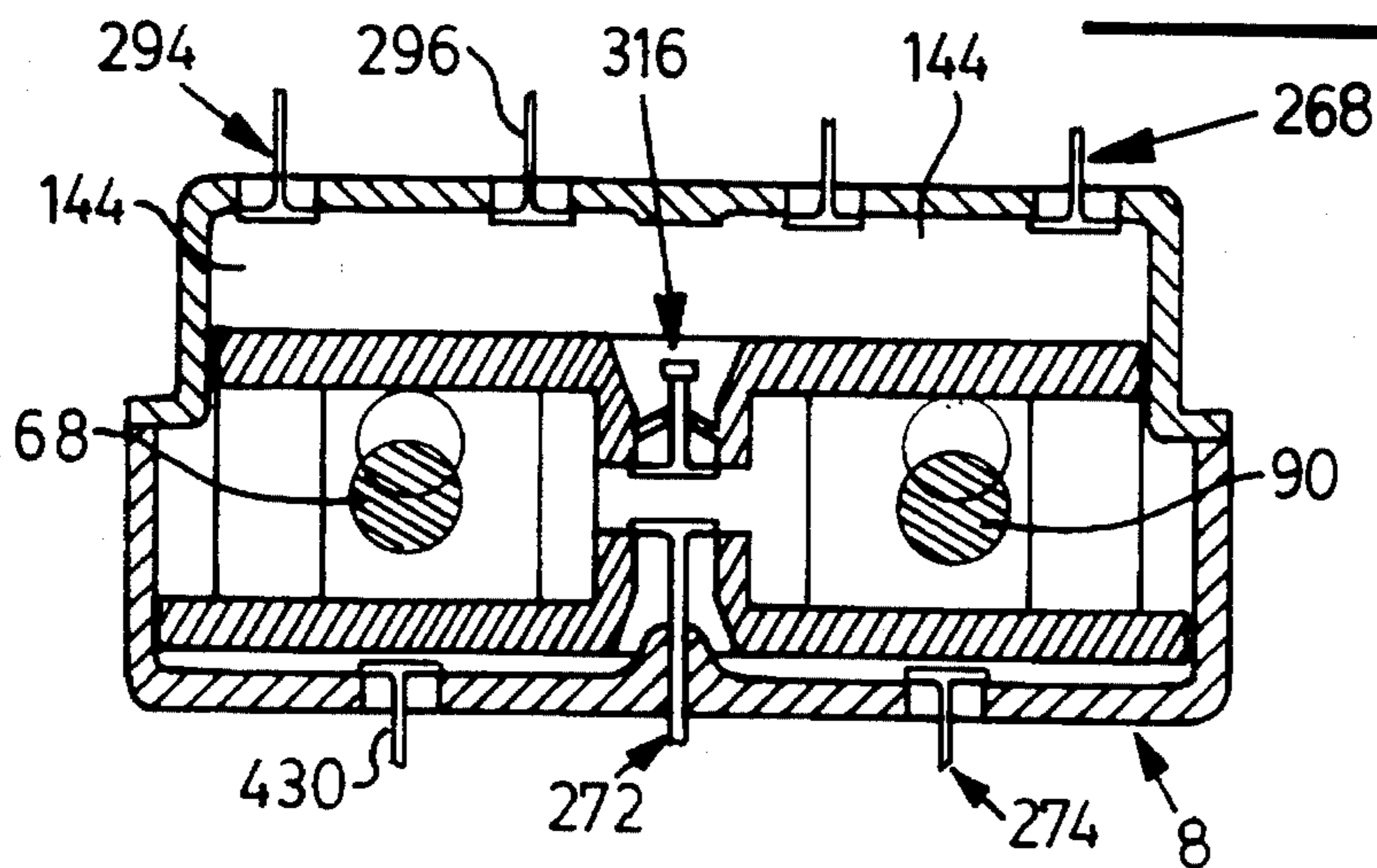


FIG- 10d

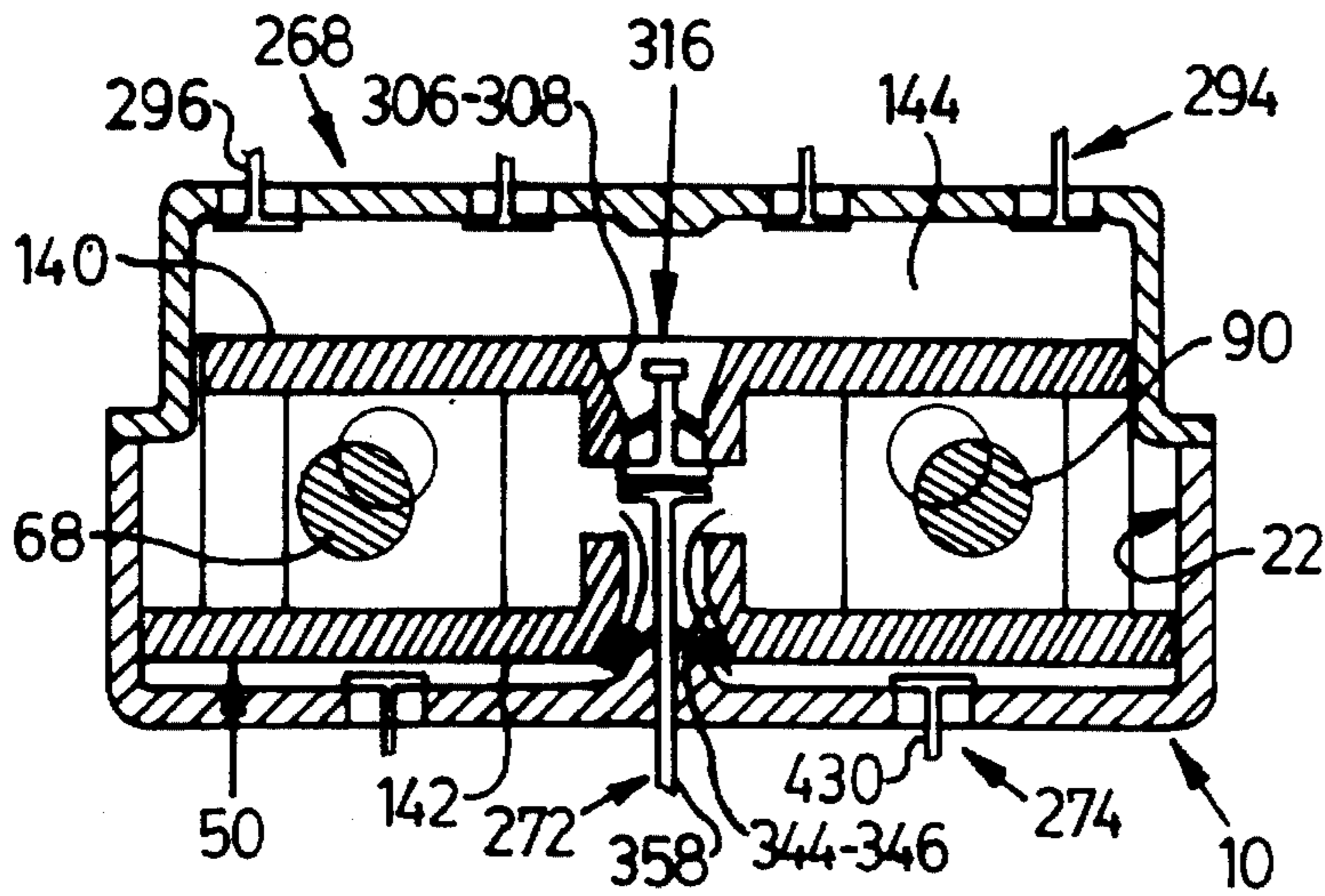


FIG- 10e

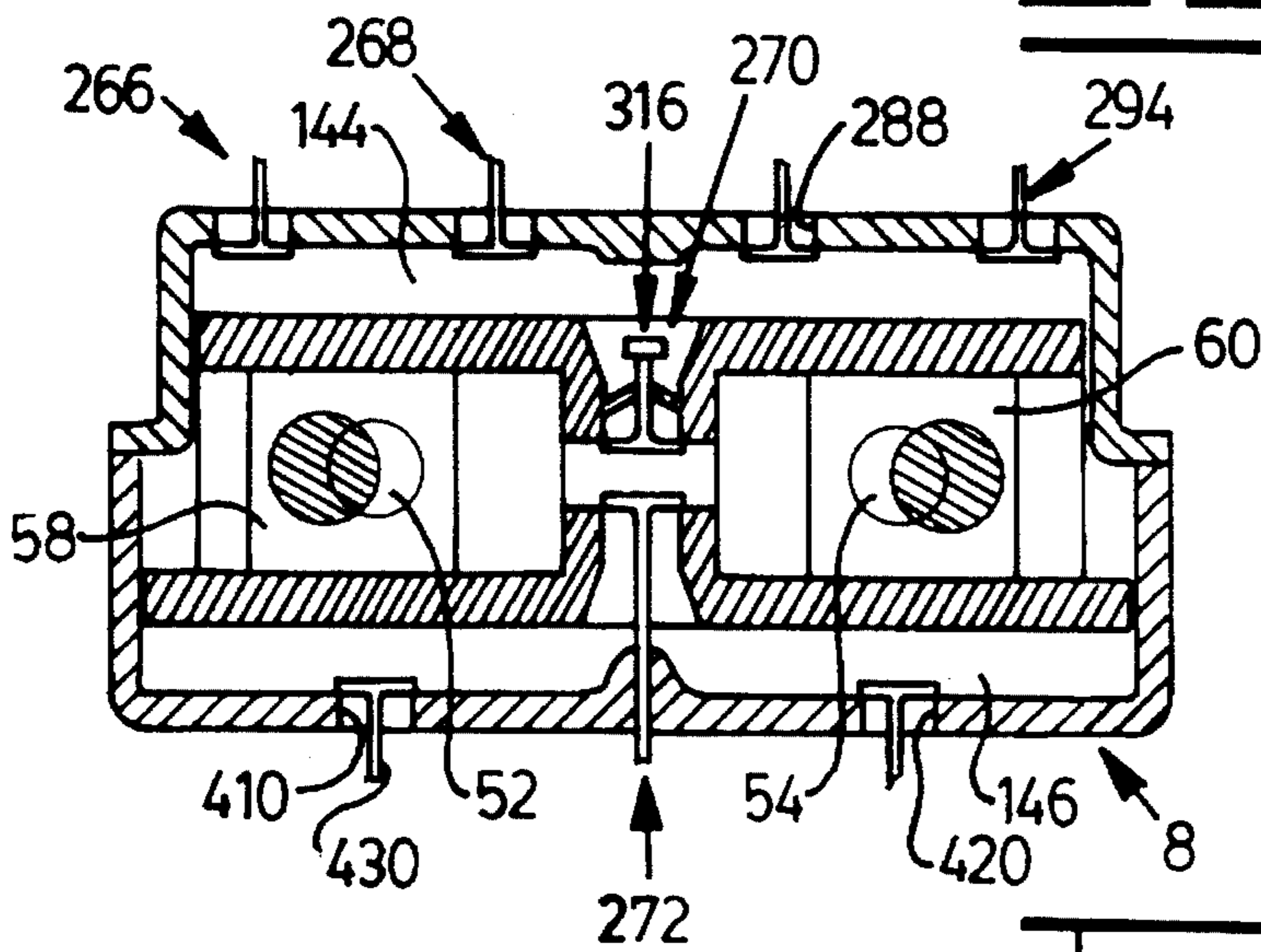
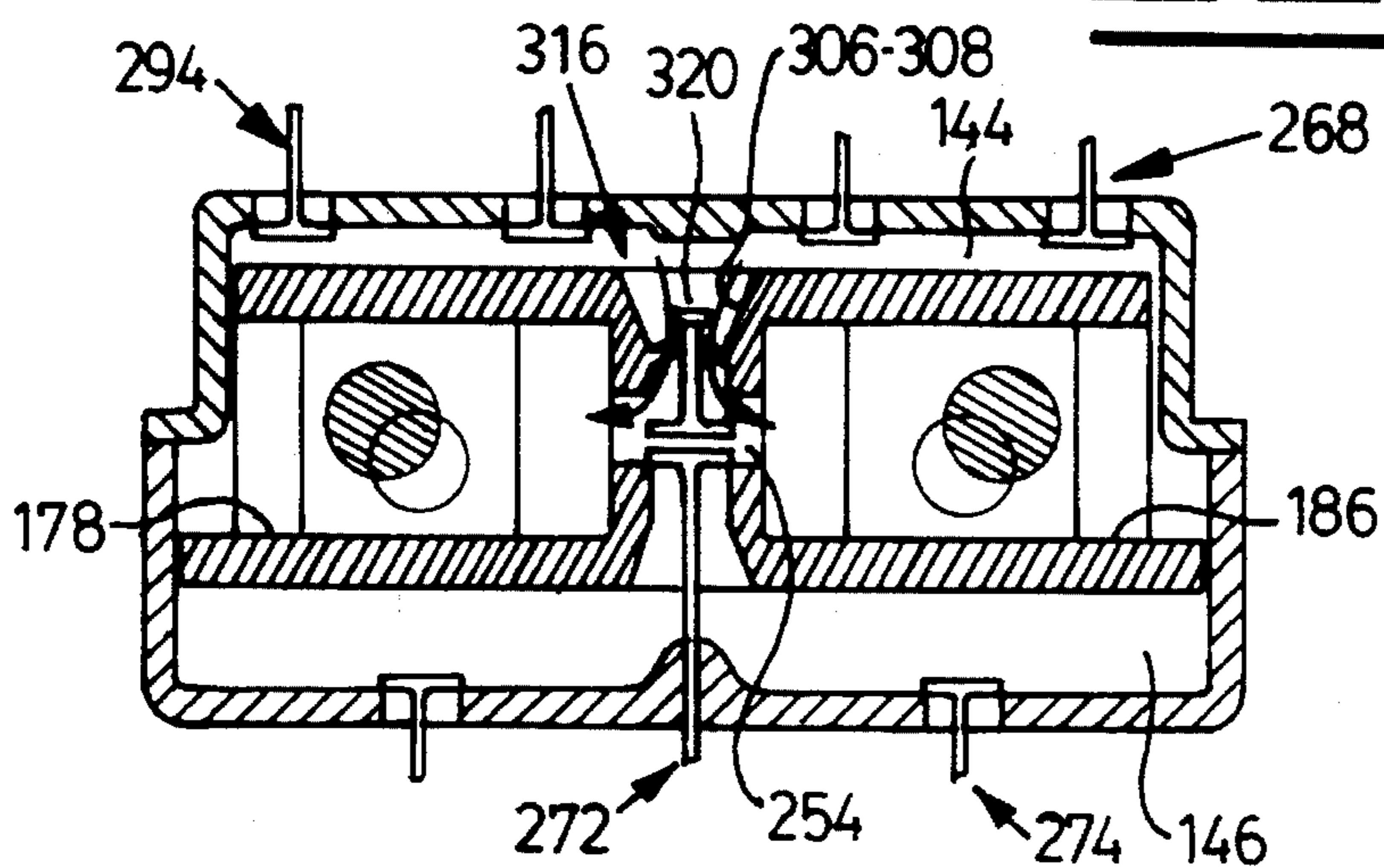


FIG- 10f





**DUAL COMPRESSION AND DUAL  
EXPANSION INTERNAL COMBUSTION  
ENGINE AND METHOD THEREFOR**

This is a divisional application of application Ser. No. 08/119,106, filed Apr. 1, 1991.

**TECHNICAL FIELD**

This invention relates generally to a compact internal combustion engine having dual compression and dual expansion and more particularly to an engine having multi-piston subassemblies preferably in back-to-back dynamically balanced units.

**BACKGROUND ART**

An internal combustion engine generally includes one or more reciprocating pistons operably connected to a crankshaft by a connecting rod to deliver energy therefrom. Such engines can operate on a 4-stroke cycle with sequentially timed phases of intake, compression, power, and exhaust, as well as 2-stroke-cycle. In a spark ignited engine a mixture of fuel and air is compressed by the piston within the closed confines of the cylinder. Near the end of the compression phase ignition occurs either by compression heating or by an ignition device to form hot burning gas which expands and drives the piston to create power.

In a diesel engine air is similarly compressed during the compression phase. Near the end of the compression phase, fuel is injected into the cylinder where it will mix with the compressed air and spontaneously ignite to form hot burning gas which, during the expansion phase of the cycle, expands against the movable piston and thereby creates power.

The last several years has seen an increasing emphasis on designing for improved fuel economy and efficiency, reduced emissions, a greater service life, and an increased power output per unit engine size.

The power of engines having similar combustion systems can be compared on the basis of their relative air flows. Conventionally there are two approaches to obtaining high air flow rates through a given engine volume. The first is the application of turbochargers to raise the density of the air entering the cylinders. The second is typified by the Wankel rotary piston engine in which a major geometric change achieves large "cylinders" in a small engine volume. The highest power density levels are achieved by combining these methods. The rotary piston engine is unsuited geometrically to withstand high cylinder pressures and to use high compression ratios so the fuel economy is poor and the potential for using turbochargers to boost the inlet air to high density is limited to levels below conventional engines.

Conventionally reciprocating engines use large bore/stroke ratio when optimized for power and a smaller bore/stroke ratio when optimized for economy. This stems from the importance of providing enough valve area for good breathing for power and a compact combustion chamber with high compression for economy. By using two stage compression and expansion processes it is possible to achieve induction in a large bore/stroke cylinder and combustion in a more compact space and so to achieve a better combination of high power and high efficiency.

It is well known that dilution of charge by recirculating exhaust gas can have a beneficial influence on flame temperature and the level of NO<sub>x</sub> emissions from an engine. Conventionally the exhaust gas subtracts from the space

available for a fresh charge of air and so this method is inappropriate for high power levels.

Accordingly what is needed is an improved internal combustion engine which is (a) compact because it has large "cylinders" for induction relative to its volume, (b) efficient because it can use high compression ratios with a compact combustion space and, (c) low on NO<sub>x</sub> emissions because it achieves high levels of exhaust retention without loss of power.

**DISCLOSURE OF THE INVENTION**

In one aspect of the present invention, a method of burning a mixture of combustible fuel and air in an engine includes a housing defining an operating chamber, a first piston assembly defining a bore is disposed in the operating chamber and defines therewith an intake chamber and an exhaust chamber. A second piston assembly is reciprocally disposed in the bore of the first piston assembly and defines therewith a combustion space. A crankshaft is rotatably supported in the housing and the second piston assembly is operatively connected to the crankshaft. The first piston assembly is moved in a first direction in the operating chamber inducting a charge of air into the intake chamber. The first piston assembly is moved in a second direction to a preselected position compressing the air in the intake chamber. The first piston assembly is moved beyond the preselected position continuing to compress the air in the intake chamber and transferring the compressed air into the combustion space and moving the second piston assembly to a preselected position compressing the air in the combustion space. During the same interval the second piston assembly moves in the bore beyond the preselected position further compressing the air in the combustion space. Ignition of fuel and air in the combustion space drives the second piston assembly to a preselected position in the bore, transmitting energy to the crankshaft. The second piston assembly continues to be driven in the bore, transmitting energy to the crankshaft and the gas is transferred to the exhaust chamber. The first piston assembly is moved in the second direction to a preselected position, expanding the gas in the exhaust chamber and transmitting energy to the crankshaft. The first piston assembly is moved in the first direction exhausting the gas from the exhaust chamber.

In a further aspect of the invention, a method of burning a mixture of combustible fuel and air in the engine includes a housing defining an operating chamber. A first piston assembly is disposed in the operating chamber and defining therewith, an intake chamber, and an exhaust chamber. A crankshaft is rotatably supported in the housing and a second piston assembly is operatively connected to the crankshaft and reciprocally disposed in a bore defined in the first piston assembly. The first piston assembly is moved in a first direction in the operating chamber inducting a charge of air into the intake chamber and reducing the volume in the exhaust chamber, exhausting the gas from the exhaust chamber. During the same interval the second piston assembly is moved in the bore compressing air in the combustion space. Ignition of fuel and air in the combustion space drives the second piston assembly to a preselected position in the bore transmitting energy of the expanded gas to the crankshaft. The first piston assembly is moved in a second direction to a preselected position compressing the air in the intake chamber. During the same interval gas expansion drives the second piston assembly in the bore transmitting energy to the crankshaft and transferring the gas to the exhaust chamber which is expanding. The first piston assem-



bly is moved beyond the preselected position continuing to compress the air and transferring the compressed air into the combustion space. During the same interval moving the second piston assembly in the bore to a preselected position and compressing the air in the combustion space while continuing moving the first piston assembly in the second direction expanding the gas in the exhaust chamber and transmitting energy to the crankshaft.

In a further aspect of the present invention, a method of injecting fuel into a combustion space associated with a piston assembly reciprocally disposed in an operating chamber includes mounting a fuel injector nozzle assembly on the piston assembly. Fuel is delivered to a pump body and the fuel is injected into the nozzle assembly by a control member connected for movement with the piston assembly.

In a further aspect of the present invention, an internal combustion engine includes a housing defining an operating chamber, and having an induction passage and a scavenge passage. A first piston assembly being reciprocally disposed in the operating chamber and defining therewith, an intake chamber and an exhaust chamber. A second piston assembly is reciprocally disposed in a bore defined in the first piston assembly and defining therewith a combustion space. Flow control means selectively communicate the induction passage with the intake chamber, the intake chamber with the combustion space, the combustion space with the exhaust chamber, and the exhaust chamber with the scavenge passage. Means are provided for introducing a combustible fuel into a combustion space.

In a further aspect of the present invention, an internal combustion engine includes a housing defining an operating chamber. A first piston assembly defining a first and second coaxial aligned bores is reciprocally mounted in the operating chamber. A second and third piston assembly is reciprocally disposed in the first and second bores and defining with the first piston assembly a combustion space. A first and second crankshaft is respectively connected to the second and third piston assemblies for delivering power in response to combustion in the combustion space.

In a further aspect of the present invention, a fuel introducing system for injecting fuel into a combustion space of an engine having a housing defining a combustion space and a piston assembly reciprocally disposed in an operating chamber includes a fuel injector nozzle assembly mounted on the piston assembly and the fuel injector means includes a control member connected for movement with the piston assembly for controllably delivering fuel to the nozzle assembly in response to reciprocation of the piston assembly.

In a further aspect of the present invention, a valve train mechanism for an engine having a housing defining an operating chamber, a piston assembly reciprocally disposed in the operating chamber includes the piston assembly defining a port and a sealing surface thereabout, and a valve including a sealing face. Support means reciprocally supports the valve on the housing for movement with the piston assembly. Valve actuating means controllably displaces the sealing face away from the sealing surface during a preselected range of movement of the piston assembly.

#### BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is an isometric view of a twin crankshaft version of an internal combustion engine constructed in accordance with the present invention with portions broken away to better illustrate details thereof;

FIG. 2 is a diagrammatic transverse cross-sectional view of a representative operating chamber including a multi-piston subassembly of the engine shown in FIG. 1 as taken along line 2—2 thereof;

FIG. 3 is a diagrammatic cross-sectional view of the engine shown in FIG. 2 taken along line 3—3 thereof;

FIG. 4 is an isometric view of a representative multi-piston subassembly of the engine shown in FIG. 2;

FIG. 5 is a diagrammatic transverse cross-sectional view of the engine constructed in accordance with the present invention taken in the direction of arrows 5—5 in FIG. 2;

FIG. 6 is a diagrammatic transverse cross-sectional view of the engine constructed in accordance with the present invention taken in the direction of arrows 6—6 in FIG. 2;

FIG. 7 is a fragmentary enlarged diagrammatic transverse cross-section view of a representative operating chamber and multi-piston subassembly, and associated intake and exhaust valve and fuel injector system of the engine;

FIG. 8 is a further enlarged diagrammatic transverse cross-section view of the upper portion of FIG. 7;

FIG. 9 is a graph illustrating the changing volumes in the intake chamber, the combustion chamber, and the exhaust chamber relative to crankshaft angle for each operating chamber and multi-piston subassembly; and

FIG. 10A through 10F schematically illustrate the relative position of the multi-piston subassembly and the associated valves within each operating chamber for various crankshaft rotational positions.

#### BEST MODE FOR CARRYING OUT THE INVENTION

Referring to FIGS. 1 and 2, an internal combustion engine 8 includes a housing 10 having a first or upper housing portion 12 and a second or lower housing portion 14 removably secured together by a plurality of fasteners or bolts 16. The upper housing portion 12 defines a pair of downwardly open, generally oblong first cavities 18 and the lower portion 14 defines a pair of upwardly open generally oblong second cavities 20. The first and second cavities 18 and 20 are arranged in an opposed and aligned relationship to form a pair of identical transversely oriented and longitudinally spaced operating chambers 22.

As best shown in FIGS. 1-3, and 5 each of the first cavities 18 is defined by a pair of generally parallel side surfaces 24 and 26, a pair of generally semicylindrical end surfaces 28 and 30 that blendingly connect together the side surfaces, and a ceiling surface 32. The first cavities 18 have a preselected width "W" in the longitudinal direction, a length "L" in the transverse direction, and a height "H" as indicated in the drawings.

As best illustrated in FIGS. 1-3 and 7 each of the second cavities 20 is defined by a pair of generally semicylindrical end surfaces 44 and 46 that blendingly connect together the side surfaces, and a bottom surface 48. In this embodiment the second cavities 20 have the same width "W" and the same height "H" as the first cavities 18, but the length "L<sub>1</sub>" of each second cavity 20 is greater than the length "L" of each first cavity 18.

#### MULTI-PISTON SUBASSEMBLY

Referring to FIGS. 1-5 each of the operating chambers 22 contains a multi-piston subassembly 50 including a first left longitudinal crankshaft 52 as shown at the left when viewing FIGS. 2 and 3, a second right longitudinal crankshaft 54, a



first or relatively large, low pressure piston assembly 56, and a pair of opposed smaller second and third high pressure piston assemblies 58 and 60.

As is shown in FIGS. 1-4, the first crankshaft 52, includes a plurality of longitudinally aligned spaced main bearing journals 62 having a central axis 66, and a pair of intermittent diametrically opposite cylindrical crankpins 68. The crankpins 68 are radially offset from the axis 66 of the main bearing journals 62. Each of the main bearing journals 62 of the first crankshaft 52 is rotatably supported between the upper and lower housing portions 12 and 14 of the housing 10, in a conventional manner, with a split sleeve bearing assembly 7D. The longitudinally orientated central axis 66 is disposed generally at a right angle to the side surfaces 24, 26, 40, and 42 of the cavities 18 and 20.

A first rear timing and balancing gear 74 is connected to a rear power take-off end 76 of the first crankshaft 52 external of the housing 10. The first gear 74 is formed with a balance weight 78 on its side face positioned approximately 180 degrees away from the adjacent crankpin 68. A second front timing and balancing gear 80 is connected to an opposite front end 81 of the first crankshaft 52 external of the housing 10. The second gear 80 is formed with a balance weight 82 on its side face positioned approximately 180 degrees away from the adjacent crankpin 68.

As is illustrated in FIGS. 2, 3, and 4 the second crankshaft 54 includes a plurality of spaced, longitudinally aligned main bearing journals 84 having a central axis 88, and a pair of intermittent, diametrically opposite cylindrical crankpins 90. The crank pins 90 are axially offset with respect to the main bearing journals 84 in a conventional manner. Each of the bearing journals 84 of the second crankshaft 54 is rotatably supported between the first and second housing portions 12 and 14 of the housing 10, in a conventional manner, with a split sleeve bearing assembly 92. The axes 66 and 88 of the first and second crankshafts 52 and 54 are generally parallel.

A third rear timing and balancing gear 96 is connected to a rear end 97 of the second crankshaft 54 external of the housing 10 and in mesh with the first rear timing gear 74. The gear 96 is formed with a balance weight 98 on its side face positioned approximately 180 degrees away from the adjacent crankpin 90. A fourth front timing and balancing gear 100 is connected to an opposite front end 101 of the second crankshaft 54 external of the housing 10 and in mesh with the second front timing gear 80. The fourth gear 100 is formed with a balance weight 102 on its side face positioned approximately 180 degrees away from the adjacent crankpin 90. The rear first and third gears 74 and 96 mesh with one another and the front second and fourth gears 80 and 100 mesh with one another to impart phased counter rotation of the first and second crankshafts 52 and 54. The balance weights 78, 82, 98, and 102 together with the counter rotation of the first and second crankshafts 52 and 54 achieves complete balance with respect to forces and couples in the longitudinal, transverse, and perpendicular directions. A rear cover 104 is removably secured to the rear of the housing 10 to enclose the first and third gears 74 and 96 and a front cover 106 is removably secured to the front of the housing to enclose the second and fourth gears 80 and 100.

As best shown in FIGS. 2, 3, and 4, the first piston assembly 56 is of generally oblong shape and is reciprocally and sealably disposed in the operating chamber 22 of the housing 10. The first piston assembly 56 includes a body 110 having a pair of generally parallel side surfaces 112 and 114,

a first or left end portion 116, and a second or right end portion 118. The left end portion 116 includes a first semicylindrical end surface 120 and a second, semicylindrical end surface 122. The second semicylindrical end surface 122 extends outwardly beyond the first semicylindrical end surface 120 to form a generally horizontal flange portion 126. The right end portion 118 also includes a first semicylindrical end surface 130 and a second semicylindrical end surface 132 with the second semicylindrical end surface 132 extending outwardly beyond the first semicylindrical end surface 130 to form a generally horizontal flange portion 134.

The body 110 of the first piston assembly 56 further includes a top working surface 140 and a bottom working surface 142. The working surfaces 140 and 142 are preferably parallel to each other and perpendicular to the side surfaces 112 and 114. The disposition of the top working surface 140 within the first cavity 18 defines an intake chamber 144 of variable volume. The disposition of the bottom working surface 142 within the second cavity 20 defines an exhaust chamber 146 of variable volume. In this specific instance the area of the bottom working surface 142 is greater than the area of the top working surface 140. The first piston assembly 56 is reciprocally moveable in the operating chamber 22 in a downward first direction, when viewing FIG. 2, increasing the volume of the intake chamber 144 and reducing the volume of the exhaust chamber 146 and in an upward second direction decreasing the volume in the intake chamber and increasing the volume in the exhaust chamber.

As best shown in FIGS. 2, 4, and 8 a band 148 extends fully around the periphery of the side surfaces 112 and 114 and the semicylindrical end surfaces 120 and 130 of the body 110 adjacent the top working surface 140. The band 148 defines a pair of ring grooves 150 that extend fully around the periphery thereof. A pair of sealing rings 152 are received in the ring grooves 150 and sealingly engage with the surfaces 24, 26, 28, and 30 of the first cavity 18.

As best shown in FIGS. 2, 4, and 7 a band 154 extends fully around the periphery of the side surfaces 112 and the semicircular side surfaces 122 and 132 of the body 110 adjacent the bottom working surface 142. The band 154 defines a pair of ring grooves 156 that extend fully around the periphery thereof. A pair of sealing rings 158 are disposed in the ring grooves 156 and sealingly engage with the surfaces 40, 42, 44, and 46 of the second cavity 20.

Referring now to FIGS. 3, 4, and 5, a pair of first and second profiled crankshaft clearance passages 160 and 162 are defined in the body 110 of the first piston assembly 56 adjacent the left end portion 116 and the right end portion 118 respectively. The first passage 160 is arranged generally perpendicular to the side surfaces 112 and 114 and coaxial aligned with the main bearing journals 62 of the first crankshaft 52. The second passage 162 is arranged generally perpendicular to the side surfaces 112 and 114 and coaxially aligned with the main bearing journals 84 of the second crankshaft 54. Each of the first and second passages 160 and 162 is spaced approximately midway between the top and bottom working surfaces 140 and 142 and parallel thereto. Defined in the side surfaces 112 and 114 of the piston body 110 about each of the passages 160 and 162 are a pair of vertically orientated, oblong stepped clearance recesses 164 and 166. The first crankshaft 52 is operatively disposed in the passage 160 and the recesses 164 and 166 without making contact therewith. The second crankshaft 54 is operatively disposed in the passage 162 and the recesses 164 and 166 without making contact therewith.



As is shown best in FIGS. 2 and 3, a first cylindrical piston bore 178 having an end surface and a central axis 182 is defined in the body 110 of the first piston assembly 56. The first piston bore 178 extends inward from the semicylindrical end surface 120 of the first end portion 116. The central axis 182 is preferably located on a first plane that is parallel to and midway between the side surfaces 112 and 114, and on a second plane that is parallel to and midway between the top and bottom working surfaces 140 and 142. The central axis 182 of the piston bore 178 intersects the main bearing journal axis 66 of the first crankshaft 52 at a right angle.

A second cylindrical piston bore 186 having an end surface 188 is defined in the body 110 of the first piston assembly 56. The second piston bore 186, having a central axis 190, extends inward from the first semicylindrical end surface 130 of the second end portion 118. The axes 182 and 190 of the piston bores 178 and 186 are coaxial. The central axis 190 of the second cylindrical piston bore 186 intersects the main bearing journal axis 88 of the second crankshaft 54 at a right angle.

The second piston assembly 58 is sealingly engaged in the first cylindrical piston bore 178 and pivotally connected directly to the crankpin 68 of the first crankshaft 52. The third piston assembly 60 is sealingly engaged in the second cylindrical piston bore 186 and pivotally connected directly to the crankpin 90 of the second crankshaft 54 and in opposed relationship with the second piston assembly 58.

As shown in FIGS. 2-4 the second and third piston assemblies 58 and 60 are identical and includes a body portion 198, a bearing cap 200, a pair of semicylindrical bearing shells 202 and 204 and a pair of fasteners or bolts 206 to removably secure the cap to the body portion 198. The body portion 198 includes a generally cylindrical head end 208 having a working surface 210 facing the respective end surfaces 180 and 188 of the bores 178 and 186 and a coupling end 212. The head end 208, as best shown in FIG. 2, defines a pair of sealing ring grooves 216 which are adapted to receive a pair of sealing rings 218 in the usual manner. The coupling end 212 defines a semicylindrical surface 220 for mounting the bearing shell 202 and the bearing cap 200 defines a semicylindrical surface 222 for mounting the bearing shell 204. Means 224 for pivotally connecting the respective second and third piston assemblies 58 and 60 directly to the crankpins 68 and 90 of the first and second crankshafts 52 and 54 includes the coupling end 212, the bearing cap 200, the bearing shells 202 and 204, and the bolts 206.

Referring to FIGS. 2, 3, and 7 a centrally located combustion space or chamber 254 is defined in the body 110 of first piston assembly 56 between the opposed working surfaces 210 of the second and third piston assemblies 58 and 60. The combustion space 254, being of variable volume, is defined by a horizontal top surface 256, a horizontal bottom surface 258, a pair of concave side surfaces 260 and 262 of the piston body 110, and the opposed working surfaces 212 of the piston assemblies 58 and 60.

#### FLOW CONTROL MEANS

The engine 10 further includes flow control means 266 as illustrated in FIGS. 1, 2, 5 and 6 for selectively communicating the induction passage passages 282 and 286 with the intake chamber 144, the intake chamber 144 with the combustion space 254, the combustion space 254 with the exhaust chamber 146, and the exhaust chamber 146 with the scavenge passages 414 and 422. The flow control means 266

include induction means 268, intake means 270, exhaust means 272, and scavenge means 274.

As shown in FIGS. 1, 2, and 5 the upper portion 12 of the housing 10 further includes a left induction air manifold 280 defining a left air induction passage 282 and a right induction air manifold 284 defining a right air induction passage 286. The ceiling surface 32 of the first portion 12 of the housing 10 defined a plurality of induction ports 288. In this specific instance there are eight induction ports 288, four of which connects the left induction passage 282 with the intake chamber 144 and four of which that connects the right induction passage 286 with the intake chamber. An annular induction valve seating surface 290 is defined about each one of the induction ports 288.

The induction means 28 operatively communicates the induction passages 282 and 286 with the intake chamber 144 via the induction passages 282 and 286 and the induction ports 288. The induction means 268 include a self opening induction poppet valve assembly 294 operatively disposed in each one of the induction port 288. Each one of the induction valve assemblies 294 includes an induction valve 296 and an induction valve spring 298. The induction valve 296 includes an induction valve stem 300, an induction head portion 302 disposed at one end of the induction valve stem and an enlarged end portion 303 disposed at an opposite end of the induction valve stem. The induction valve head portion 302 defines an annular induction valve sealing face 304 being of a dimension sufficient for sealingly seating of the induction valve 296 on the induction valve Seating surface 290. The induction valve spring 298 urges the induction valve 296 against the induction valve seating surface 290 until the induction valve head portion 302 is moved from the induction valve seating surface. The induction valve spring 298 is located between the enlarged end 303 of the induction valve 296 and an induction valve guide web 305 in each of the induction ports 288 and is operative to urge the induction valve 296 against the respective induction valve seating surface 290. Although simple self opening popper induction valve assemblies are shown it is recognized that other induction valve arrangements are possible with actuation, for example, by mechanical, electrical, or other means.

As best shown in FIGS. 2, 6, 7, and 8 the piston body 110 defines a pair of first and second profiled intake ports 306 and 308 that are longitudinally aligned between the side surfaces 112 and 114 of the body. The intake ports 306 and 308 extends between the top working surface 140 and the top surface 256 of the combustion space 254 and have a central axes 310 and 312 respectively. The central axes 310 and 312 are generally perpendicular to the top working surface 140 and approximately midway between the semi-circular end surfaces 120 and 130 of the body 110. As best shown in FIG. 7 an annular seating surface 134 is defined in the top surface 256 of the combustion space 254 about each one of the intake ports 306 and 308.

The intake means 270 operatively communicates the intake chamber 144 with the combustion space 254 via the first and second ports 306 and 308. The intake means 270 in this specific instance, includes an intake poppet valve assembly 316 of the self opening type, operatively mounted in each one of the intake ports 306 and 308 of the piston body 110. The intake poppet valve assembly 316 includes an intake valve 320 and a spring 322. The intake valve 320 includes a intake valve stem 324 and an intake valve head portion 326 disposed at the end of the intake valve stem. The intake valve head portion 326 defines an annular intake valve sealing face 328 of a dimension sufficient for sealingly



seating of the intake valve sealing face on the intake valve seating surface 314. The intake valve spring 322 urges the intake valve 320 against the intake valve seating surface 314 until the intake valve head portion 326 is moved from the intake valve seating surface. The intake valve spring 322 is located between an enlarged end 330 of the intake valve stem 342 and an intake valve guide web 332 in each of the intake ports 306 and 308 and is operative to urge the intake valve 320 against the respective intake valve seating surface 314. Although simple self opening poppet intake valve assemblies 316 are shown it is recognized that other intake valve arrangements are possible with actuation, for example, by mechanical, electrical, or other means.

As shown in FIGS. 2, 6 and 7 the piston body 110 further defines a pair of first and second profiled exhaust ports 344 and 346 having a central axis 348 and 350 respectively. The exhaust ports 344 and 346 are longitudinally aligned between the side wall 112 and 114 of the body 110 and extend between the bottom working surface 142 and the bottom surface 258 of the combustion space 254. The central axes 348 and 350 of the exhaust ports 344 and 346 are generally perpendicular to the bottom working surface 142 and approximately midway between the semicircular end surfaces 122 and 132 of the piston body 110. The central axis 348 of first exhaust port 344 is axially aligned with the central axis 310 of first intake port 306 and the central axis 350 of the second exhaust port 346 is axially aligned with the central axis 312 of second intake port 308. An annular exhaust valve seating surface 352 is defined in the bottom surface 258 of the combustion space 254 and about each one of the exhaust ports 344 and 346.

The exhaust means 272 selectively communicates the combustion space 254 with the exhaust chamber 146 via the first and second exhaust ports 344 and 346. The exhaust means 272 includes an exhaust valve operating mechanism 356. The exhaust valve operating mechanism 356 includes an exhaust valve 358 operatively mounted in each one of the exhaust ports 344 and 346 and an exhaust valve support means 360 for reciprocally supporting the exhaust valves 358 on the housing 10 for movement with the low pressure piston assembly 56. The exhaust valves 358 each include an exhaust valve stem 366 and an exhaust valve head portion 368 disposed at the end of the exhaust valve stem. The exhaust valve head portion 368 defines an annular exhaust valve sealing face 370 of a dimension sufficient for sealingly seating of the exhaust valve sealing face on the exhaust valve seating surface 352 of the piston body 110. The exhaust valve support means 360 includes an exhaust valve sleeve bearing or exhaust valve guide 376 mounted in an exhaust valve pump cylinder 378 defined in the bottom surface 48 of the lower portion 14 of the housing 10 and a cylindrical exhaust valve pump piston 380 mounted on an end of the exhaust valve 358 opposite the exhaust valve head portion 368. The exhaust valve guide 376 encompasses the exhaust valve stem 366 and the exhaust valve pump piston 380 is adapted for reciprocal sliding movement in the exhaust valve pump cylinder 378. An outer exhaust valve pump chamber 382 is defined in the exhaust valve pump cylinder 378 outwardly of the exhaust valve pump piston 380. An inner exhaust valve spring chamber 384 is defined in the exhaust valve pump cylinder 378 inwardly of the exhaust valve pump piston 380. An exhaust valve spring 386 is disposed about the exhaust valve stem 366 in the exhaust valve spring chamber 384 and extends between the exhaust valve guide 376 and the exhaust valve pump piston 380. The exhaust valve actuating spring 386 urges the exhaust valve sealing face 370 of the exhaust valve 358 against the exhaust

valve seating surface 352 until the exhaust valve head portion 368 is moved away from exhaust valve seating surface.

As best shown in FIGS. 1, 2, and 5 the lower portion 14 of the housing 10 defines a pair of left profiled scavenge ports 410 that connect the exhaust chamber 146 with a first scavenge passage 414 in a left scavenge manifold 416. An annular first scavenge valve seating surface 418 is defined about each of the left scavenge ports 410. The lower portion 14 of the housing 10 further defines a pair of right scavenge ports 420 that connects the exhaust chamber 146 with a second scavenge passage 422 defined in a right scavenge manifold 424. An annular second scavenge valve surface 426 is defined about each of the right scavenge ports 420.

The scavenge means 274 selectively and operatively communicates the exhaust chamber 146 with the left and right scavenge manifolds 416 and 424 via the two pair of scavenge ports 410 and 420 and the first and second scavenge passages 414 and 422. The scavenge means 274 includes a scavenge valve operating mechanism 428. The scavenge valve operating mechanism 428 includes a scavenge valve 430 associated with each one of the scavenge ports 410 and 420 and scavenge valve support means 432 for reciprocally supporting the scavenge valves on the housing 10. The scavenge valve 430 includes a scavenge valve stem 434 and a scavenge valve head portion 436 disposed at the end of the scavenge valve stem. The scavenge valve head portion 436 defines an annular scavenge valve sealing face 438 of a dimension sufficient for sealingly seating of the scavenge valve sealing face on the respective scavenge valve seating surfaces 418 and 426. The scavenge valve support means 432 includes a scavenge valve sleeve bearing or scavenge valve guide 444 mounted in a scavenge valve pump cylinder 446 defined in the housing 10 and a cylindrical scavenge valve pump piston 448 mounted on an end of the scavenge valve stem 434 opposite the scavenge valve head portion 436. The scavenge valve guide 444 encompasses the scavenge valve stem 434 and the scavenge valve pump piston 448 is adapted for reciprocal sliding movement in the scavenge valve pump cylinder 446. An scavenge valve pump chamber 450 is defined in the scavenge valve pump cylinder 446 outwardly of the scavenge valve pump piston 448. An scavenge valve spring chamber 452 is defined in the scavenge valve pump cylinder 446 inwardly of the scavenge valve pump piston 448. A scavenge valve coil spring 454 is disposed about the scavenge valve stem 434 in the scavenge valve spring chamber 452 and extends between the scavenge valve guide 444 and the scavenge valve pump piston 448. The scavenge valve spring 454 urges the scavenge valve seating face 438 of the scavenge valve 430 against the respective scavenge seating surfaces 418 and 426 until the scavenge valve head portion 436 is moved away from the scavenge valve seating surface.

#### FUEL INTRODUCING SYSTEM

Referring to FIGS. 7 and 8 of the drawings, a fuel introducing system 455 is shown. The fuel introducing system 455 includes a fuel injector nozzle assembly 456 mounted on the first piston assembly 56 and communicates with the combustion space 254 and fuel injection means 458 including communication means 463 connected for movement with the first piston assembly 56 for controllably delivering fuel to the fuel injector nozzle assembly 456 in response to reciprocation of the first piston assembly 56. The communication means 463 includes a control member 464 and the fuel injector means 458 includes a fuel pump



assembly 460. The fuel pump assembly 460 includes a pump body 462 in which the plunger or control member 464 is reciprocally positioned. The pump body 462 is removably secured by a pair of fasteners or bolts 466 in a mounting bore 468 defined in the upper portion 12 of the housing 10. The mounting bore 468 has a central axis 470 that is preferably located on a first plane that is parallel to and midway between the side surfaces 24 and 26 of the operating chamber 22 and on a second plane that is parallel to and midway between the semicylindrical end surfaces 28 and 44.

The pump body 462 defines a fuel pump cylinder 474 having a central axis 475 that is coaxial with the axis 470 of the mounting bore 468. The control member 464 includes an outer rod portion 476 that extends through an outer rod bore 478 defined in the pump body 462, an intermediate fuel pump piston portion 480, and an inner rod portion 482 that extends through an inner rod bore 484 defined in the pump body. The cross-sectional areas of the outer and inner rod portions 476 and 482 within the fuel pump cylinder 474 are identical. The fuel pump piston portion 480 includes an outer control end surface 488, a cylindrical land surface 490 of a predetermined axial length, and an inner control end surface 492. An outer fuel pump chamber 494 is defined in the fuel pump cylinder 474 outwardly of the fuel pump piston portion 480 and an inner fuel pump chamber 498 is defined in the fuel pump cylinder inwardly of the fuel pump piston portion. The outer fuel pump chamber 494 is supplied fuel from a source 500 via a fuel line 502 and a transverse passage 504 defined in the pump body 462. A fuel transfer passage 506 is defined in the pump body 462 interconnecting the outer and inner fuel pump chambers 494 and 498. A first fuel pump port 510 defined in the pump body 462 connects the transfer passage 506 to the fuel pump cylinder 474. A passage blocking piston 514 of a solenoid actuated valve 516 is located in the transfer passage 506 between the outer fuel pump chamber 494 and the connection of the first fuel pump port 510 and is operative to selectively block fluid flow therethrough. A fill passage 518 is defined in the pump body 462 connecting the transverse passage 504 with the fuel pump cylinder 474. A second fuel pump port 522 defined in the pump body 462 connects the fuel pump cylinder 474 to the fill passage 518. The second port 522 is spaced axially inwardly of the first fuel pump port 510.

A profiled nozzle bore 526, opening into the combustion space 254, is defined in the first piston assembly 56. The nozzle bore 526 has an axis co-axial with the central axis 470 of mounting bore 468. The injector nozzle assembly 456 is located in the nozzle bore 526 and operative to inject fuel into the combustion space 254. The nozzle assembly 456 includes a fuel injector body 530 defining a flow charge passage 532, an injector valve bore 534, and spray orifice means 536. An injector valve spring 538 biases an injector valve 540 that is reciprocally disposed in the injector valve bore 534.

The inner rod portion 482 of the control member 464 includes an enlarged end portion 544 threadably secured to the first piston assembly 56 to impart reciprocal movement of the fuel pump piston 480 in the fuel pump cylinder 474 with reciprocal movement of the first piston assembly 56. The end portion 544 includes a counterbore 546 that encompasses the injector body 530 of the injector nozzle assembly 456 capturing the injector nozzle assembly in the nozzle bore 526. The inner rod portion 482 further includes an axial supply passage 548 that connects the inner fuel pump chamber 498 of the fuel pump cylinder 474 to the flow charge passage 532 in the injector body 530.

## EXHAUST VALVE ACTUATION

Referring to FIGS. 2, 6 and 7 and specifically FIG. 7, the exhaust means 272 further includes exhaust valve actuation means 560 for controllably displacing the exhaust valve sealing face 370 of each exhaust valve 358 away from its respective exhaust valve sealing surface 352 during a pre-selected range of movement of the first piston assembly 56 in the operating chamber 22. The exhaust valve actuation means 560 includes transfer means 562 for transferring hydraulic fluid between an exhaust valve transfer pump cylinder 564 defined in the pump body 462 and the exhaust valve pump chambers 382 associated with each of the exhaust valves 358. The transfer pump cylinder 564 has an axis that is coaxial with the axis 470 of the mounting bore 468 for the pump body 462. The outer rod portion 476 of the control member 464 extends into the exhaust valve transfer pump cylinder 564. A cylindrical transfer pump piston 566 is mounted on an end of the outer rod portion 476 for reciprocal movement therewith. A transfer pump chamber 568 is defined in the transfer pump cylinder 564 outwardly of the transfer pump piston 566. The cross-sectional area of the transfer pump chamber 568 is equal to the combined cross-sectional areas of the exhaust valve pump chambers 378 associated with each of the exhaust valves 358. A transfer conduit 570 interconnects the transfer pump chamber 568 with each of the exhaust valve pump chambers 382.

As shown in FIG. 7 the exhaust valve actuation means 560 further includes an exhaust valve actuator cylinder assembly 574. The exhaust valve actuator cylinder assembly 574 includes an exhaust valve actuator body 576 defining an exhaust valve actuator bore 578 with an exhaust valve actuator piston 580 slidably disposed in the exhaust valve actuator bore. An exhaust valve actuator fluid chamber 582 having a preselected volume is defined in the exhaust valve actuator bore 578 between the exhaust valve actuator piston 580 and one end of the exhaust valve actuator chamber. An exhaust valve actuator piston rod 584 is connected to the exhaust valve actuator piston 580 opposite the exhaust valve actuator chamber 582. An exhaust valve actuator cam follower 586 is connected at an end of the exhaust valve actuator rod 584 and rides on a exhaust valve cam 588 driven by the engine 8. The exhaust valve cam 588 makes one revolution for each revolution of the first and second crankshafts 52 and 54. An exhaust valve actuator spring 590 is disposed in the exhaust valve actuator chamber 582 between the exhaust valve actuator piston 580 and an end of the exhaust valve actuator chamber biases the exhaust valve cam follower 586 against the exhaust valve cam 588. The exhaust valve actuator chamber 582 is connected to the transfer conduit 570 by a branch conduit 592.

## SCAVENGE VALVE ACTUATION

Referring to FIGS. 2 and 5 the scavenge means 274 further includes scavenge valve actuation means 594 for controllably displacing the scavenge valve sealing face 438 of each scavenge valve 430 away from its respective scavenge valve seating surfaces 418 and 426 at a preselected time. The scavenge valve actuation means 594 includes a scavenge valve actuator assembly 596. The scavenge valve actuator assembly 596 includes a scavenge valve actuator body 598 defining a scavenge valve cylindrical actuator bore 600 with an scavenge valve actuator piston 602 slidably disposed in the scavenge valve actuator bore. A scavenge valve actuator fluid chamber 604 having a preselected volume is defined in the scavenge valve actuator bore 602



between the scavenge valve actuator piston 602 and one end of the scavenge valve actuator chamber. A scavenge valve actuator piston rod 606 is connected to the scavenge valve actuator piston 602 opposite the scavenge valve actuator chamber 604. A scavenge valve actuator cam follower 608 is connected to an end of the scavenge valve actuator piston rod 606 and rides on a scavenge valve cam 610 driven by the engine 8. The scavenge valve cam 610 makes one revolution for each revolution of the first and second crankshafts 52 and 54. A scavenge valve actuator spring 612 disposed in the scavenge valve actuator chamber 604 between the scavenge valve actuator piston 602 and an end of the scavenge valve actuator chamber biases the scavenge valve actuator cam follower 608 against the scavenge valve cam 610. A conduit 614 connects the scavenge valve actuator chamber 604 with each of the scavenge valve pump chambers 450 associated with each of the scavenge valves 430.

#### Industrial Applicability

In operation the pair of opposed high pressure piston assemblies 58 and 60 of the dual compression and dual expansion internal combustion engine 8, are directly mounted on the respective pair of crankpins 68 and 90 of the geared together, counter rotating, crankshafts 52 and 54. The high pressure piston assemblies 58 and 60 are reciprocally and sealably disposed in their respective bores 178 and 186 of the low pressure piston assembly 56 and driven by combustion in the combustion space 254 transferring energy to the crankshafts 52 and 54. The orbital movement of the high pressure piston assemblies 58 and 60 and the pressure caused by the expanding exhaust gas in the exhaust chamber 146 acting on the bottom working surface 142 of the low pressure piston assembly 56 reciprocally drives the low pressure piston assembly in the operating chamber 22. Other operating chambers 22, with multiple-piston subassemblies 50 can be added along the crankshafts 52 and 54 by adding additional crankpins 68 and 90, flow control means 226, and fuel introducing systems 455 in the manner of the additional cylinders of an in-line conventional engine. Alternatively, the multi-piston subassembly 50 may have only one crankshaft 52 and one high pressure piston assembly 58 directly mounted on the crankshaft 52 and disposed in one cylindrical piston assembly bore 178 defined in the body 110 of the low pressure piston assembly 56. As in the preceding arrangement, other operating chambers 22, with alternative multi-piston subassemblies 50 can be added along the crankshaft 52 by adding additional crankpins 68, flow control means 226, and fuel introducing systems 455.

There are three varying volume chambers within each operating chamber 22. The disposition of the top surface 140 of the low pressure piston assembly 56 within the first cavity 18 defines the intake chamber 144 of varying volume. The disposition of the second and third piston assemblies 58 and 60 within their respective bores 178 and 186 of the low pressure piston assembly 56 defines the variable volume combustion chamber 254. The disposition of the bottom working surface 142 of the low pressure piston assembly 56 in the second cavity 20 defines the variable volume exhaust chamber 146. Air, fuel, and gas of combustion move from the intake chamber 144 to the exhaust chamber 146 through the intake means 270 and the exhaust means 272 in the low pressure piston assembly 56, but in the process the air and fuel are compressed and combusted and gas is expanded in the combustion space 254 between the high pressure piston assemblies 56 and 60.

The operating processes or steps of engine 8, identified as A through I, are timed as shown in FIG. 9. A complete cycle from start of air entry into the intake chamber 144 to the exit

of the exhaust gas of the same charge from the exhaust chamber 146 takes approximately 900 degrees of rotation of the crankshafts 52 and 54 during which the intake chamber, the combustion chamber 254, and the exhaust chamber 146 each undergoes five "strokes".

Referring to FIGS. 1-3 and 9, step A begins at approximately -450 degrees of rotation of the crankshafts 52 and 54 and ends at approximately -270 degrees for a duration of approximately 180 degrees. During step A the low pressure piston assembly 56 is moved in the first direction in the operating chamber 22, away from the ceiling 32 of the intake chamber 144 increasing the volume of the intake chamber and inducing a charge of air through the induction passages 282 and 286 of the left and right induction manifolds 280 and 284, and the self opening induction poppet valve assemblies 29 disposed in each of the induction ports 288. Movement of the low pressure piston assembly 56 in the intake chamber 144 lowers the pressure in the intake chamber below the pressure in the the left and right induction passages 282 and 286. The higher pressure in the induction passages 282 and 286 acts on the induction valve head portions 302 within the intake chamber 144 overcoming the bias of the induction valve springs 298 moving the induction valve sealing faces 304 away from the induction valve seating surfaces 290. The intake valves 320 of the poppet intake valve assembly 316 disposed in the first and second intake ports 306 and 308 of the low pressure piston assembly 56 are maintained in the closed position by high pressure in the combustion chamber 254. The high pressure is created by sequential compression of air, combustion, and expansion of burning gas from steps D, E, and F of another one of the plurality of cycles occurring during the same time interval. The high pressure acts on the ends of the intake valve head portions 326 within the combustion chamber 254, forcing the intake valve sealing face 328 against the intake valve sealing surface 314.

Step B begins at approximately -270 of crankshafts 52 and 54 rotation and ends at approximately -180 degrees for a duration of approximately 90 degrees. During step B the low pressure piston assembly 56 is moved in the second direction towards the ceiling 32 of the intake chamber 144 compressing the charge of inducted air in the intake chamber. The induction valves 296 of the induction valve assemblies 294 are maintained sealingly seated against the induction valve seating surfaces 314 by the pressure created by the air being compressed within the intake chamber 144 acting on the ends of the induction valve head portions 302 within the intake chamber 144. During this interval the pressure within the combustion space 254 is greater than the pressure created by the compression of the air in the intake chamber 144 and the poppet intake valves 316 are maintained in the closed position. The pressure in the combustion chamber 254 is caused by the expansion of burning gas in the combustion chamber 254 from step G of another one of the plurality of cycles occurring during the same time interval. The high pressure acts on the ends of the intake valve head portions 326 of the intake valves 320 within the combustion chamber 254 forcing the intake valve sealing face 328 against the intake valve sealing surface 314.

Step C begins at approximately -180 degrees of rotation of the crankshafts 52 and 54 and ends at approximately -90 degrees for a duration of approximately 90 degrees. During step C, the low pressure piston assembly 56 is moved further in the second direction, continuing to compress the charge of induction air in the intake chamber 144 while transferring the charge of compressed air to the combustion space. During this interval the pressure of compression in the



intake chamber 144 is greater than the pressure in the combustion chamber 254 and the bias of the intake valve springs 322 and the intake valves 320 are forced away from the intake valve seating surfaces 314 by the pressure of compression acting on the surfaces of the intake valve head portions 326 adjacent the intake valve stems 324. During the same interval, the second and third piston assemblies 58 and 60 are moved in their respective bores 178 and 186 compressing the charge of compressed air in the combustion space 254. The exhaust valves 358 are closed and the exhaust valve sealing faces 370 are maintained against their respective seating surfaces 352 by the bias of the exhaust valve springs 386 and the rising pressure of compression in the combustion space 254 acting on the ends of the exhaust valve head portions 368 within the combustion space 254.

Step D begins at approximately -90 degrees of rotation of the crankshafts 52 and 54 and ends at approximately 0 degrees for a duration of approximately 90 degrees. During step D the second and third piston assemblies are moved further in their respective bores 178 and 186 compressing the charge of compressed air in the combustion space 254. During this interval, the intake valves 320 and the exhaust valves 358 are closed by the pressure of compression in the combustion space 254 being greater than the pressure in intake chamber 144 and the pressure in the exhaust chamber 146. The pressure of compression acts on the ends of intake valve head portions 326 and the exhaust valve head portions 368 within the combustion chamber 254 maintaining the intake valve sealing faces 328 and the exhaust valve sealing faces 370 against their respective intake valve seating surface 314 and exhaust valve seating surface 352.

Step E begins at approximately 0 degrees of rotation of the crankshafts 52 and 54 and ends at approximately 50 degrees for a duration of approximately 50 degrees. During step E, fuel is introduced into the combustion space 254 at approximately the beginning of the time interval to form a mixture of fuel and air which auto ignites forming expanding exhaust gas driving the high pressure piston assemblies 58 and 60 apart transmitting energy to the crankshafts 52 and 54. During this interval the pressure in the combustion chamber 254 caused by combustion is greater than the pressure in the intake chamber 144 and the exhaust chamber 146. The pressure of combustion acts on the ends of intake valve head portions 326 and the exhaust valve head portions 368 within the combustion chamber 254 maintaining the intake valve sealing faces 328 and the exhaust valve sealing faces 370 against their respective intake valve seating surface 314 and exhaust valve seating surface 352.

Step F begins at approximately 50 degrees of rotation of the crankshafts 52 and 54 and ends at approximately 90 degrees for a duration of approximately 40 degrees. During step F the high pressure piston assemblies 58 and 60 continue to be driven apart in their respective bores 178 and 186 by the pressure of the expanding exhaust gas, transmitting energy to the crankshafts 52 and 54. During this interval the pressure in the combustion chamber 254 is greater than the pressure in the intake chamber 144 and the exhaust chamber 146. The pressure caused by the expanding exhaust gas acts on the ends of intake valve head portions 326 and the exhaust valve head portions 368 within the combustion chamber 254, maintaining the intake valve sealing faces 328 and the exhaust valve sealing faces 370 against their respective intake valve seating surfaces 314 and exhaust valve seating surfaces 352.

Step G begins at approximately 90 degrees of rotation of the crankshafts 52 and 54 and ends at approximately 180 degrees for a duration of approximately 90 degrees. During

step G the high pressure piston assemblies 58 and 60 continue to be driven apart in their respective bores 178 and 186 by the pressure of the expanding exhaust gas transmitting energy to the crankshafts 52 and 54 while at the same time the expanding exhaust gas is being transferred to the exhaust chamber 146. During this interval the low pressure piston assembly 56 is being moved in the second direction increasing the volume of the exhaust chamber 146 while compressing inducted air in the intake chamber 144 from step B of yet another one of the plurality of cycles. The pressure of the expanding gas in the combustion chamber 254 is greater than the pressure caused by compression of the inducted air in the intake chamber 144. The pressure of the expanding gas in the combustion chamber 254 acts on the ends of intake valve head portions 326 within the combustion chamber, maintaining the intake valve sealing faces 328 against the intake valve seating surfaces 314. The exhaust valve actuation means 560 controllably displaces the exhaust valve sealing faces 370, of the exhaust valves 358, away from their respective exhaust valve seating surfaces 352 allowing the transfer of the expanding exhaust gas to the exhaust chamber 146. The scavenge valves 430 are closed during step G, and the scavenge valve sealing surfaces 438 are maintained against their respective scavenge valve seating surfaces 418 and 426 by the pressure of the expanding exhaust gas in the exhaust chamber 146.

Step H begins at approximately 180 degrees of rotation of the crankshafts 52 and 54 and ends at approximately 270 degrees, for a duration of approximately 90 degrees. During step H the high pressure piston assemblies 58 and 60 are moved in their respective bores 178 and 186, compressing air in the combustion chamber 254 from step C of the yet another one of the plurality of cycles occurring during the same interval. The exhaust valves 358 are closed and the exhaust valve sealing faces 370 are maintained against their respective seating surfaces 352 by the bias of the exhaust valve springs 386 and the rising pressure of compression in the combustion space 254 acting on the ends of the exhaust valve head portions 368 within the combustion space 254. The scavenge valves 430 are closed, and the scavenge valve sealing surfaces 438 are maintained against their respective scavenge valve seating surfaces 418 and 426 by the pressure of the expanding exhaust gas in the exhaust chamber 146. The pressure caused by the expansion of the exhaust gas in the exhaust chamber 146, assists in driving the low pressure piston assembly 56 in the second direction. Expansion of the exhaust gas is controllably achieved in the exhaust chamber 146 in a manner to reduce the exhaust pressure to be essentially near or at scavenge passages 414 and 422 pressure at the end of the step H.

Step I begins at approximately 270 degrees of rotation of the crankshafts 52 and 54 and ends at approximately 450 degrees for a duration of approximately 180 degrees. During step I the exhaust valves 358 are maintained in a closed position by high pressure in the combustion chamber 254. The high pressure is created by sequential compression of air, combustion, and expansion of burning gas from steps D, E, and F of the yet another one of the plurality of cycles occurring during the same interval. The high pressure acts on the ends of the intake valve head portions 326 within the combustion chamber 254, forcing the intake valve sealing face 328 against the intake valve seating surface 314. The scavenge valve actuation means 594 controllably displaces the scavenge valve sealing face 438 of each scavenge valve 430 away from its respective scavenge valve seating surface 418 and 426, allowing the scavenge of the exhaust gas from the exhaust chamber 146 by way of the first and second



scavenge passages 414 and 422. During this interval the low pressure piston assembly 56 is being moved in the first direction reducing the volume of the exhaust chamber 146 and scavenging the exhaust chamber.

Each individual chamber 144, 254, and 146 of the engine 8, sees its cycle repeated every crankshaft revolution, so in that respect the engine is more like a two-stroke engine. FIGS. 10a through 10f schematically illustrates relative positions of the multi-piston subassembly 50 and the flow control means 266 within the operating chamber 22, at specific locations during one complete rotation of the crankshafts 52 and 54. The first 180 degrees of the crankshafts 52 and 54 rotation are identified as period or step X in FIG. 9. FIG. 10a schematically illustrates approximately the -450 degree position of the crankshafts 52 and 54 or the start of the step X as indicated in FIG. 9. FIG. 10b schematically illustrates approximately the -360 degree position of crankshafts 52 and 54. FIG. 10c schematically illustrates approximately the -270 degree position of crankshafts 52 and 54. During the time interval of step X, the low pressure piston assembly 56 is moved in the first direction in the operating chamber 22 increasing the volume of the intake chamber 144, inducting a charge of air into the intake chamber 144 and reducing the volume in the exhaust chamber 146, exhausting a charge of exhaust gas from the exhaust chamber 146. During the same interval the high piston assemblies 58 and 60 are moved in the bores 178 and 186 compressing another charge of air in the combustion space 254. As illustrated in FIG. 10b, at approximately -360 degrees of crankshafts 52 and 54 rotation, fuel is introduced into the combustion space 254 forming a combustible mixture of fuel and air which auto ignites forming expanding exhaust gas driving the high pressure piston assemblies 58 and 60 in their respective bores 178 and 186 and transmitting the energy to the crankshafts 52 and 54.

The next 90 degrees of the crankshafts 52 and 54 rotation is identified as a period or step Y in FIG. 9. FIG. 10d schematically illustrates approximately the -225 degree position of the crankshafts 52 and 54. During the time interval of step Y, the low pressure piston assembly 56 is moved in the second direction compressing the charge of air in the intake chamber 144. During the same time interval the high pressure piston assemblies 58 and 60 continue to be driven in their respective bores 178 and 186 transmitting energy to the crankshafts 52 and 4 while transferring the expanding exhaust gas to the exhaust chamber 146.

The next 90 degrees of rotation of the crankshafts 52 and 54 is identified as a period or step Z in FIG. 9. FIG. 10e schematically illustrates approximately the -180 degree position of the crankshafts 52 and 54 or start of the step Z. FIG. 10f schematically illustrates approximately the -135 degree position of crankshafts 52 and 54. During step Z the low pressure piston assembly 56 continues to be driven in the second direction compressing the charge of air in the intake chamber 144 while transferring the charge of compressed air into the combustion space 254. During the same interval, the high pressure piston assemblies 58 and 60 are moved in their respective bores 178 and 186 further compressing the charge of compressed air in the-combustion space 254. The pressure caused by the expansion of the exhaust gas in the exhaust chamber assists in driving the low pressure piston assembly 56 in the second direction transmitting energy to the crankshafts 52 and 54.

The exhaust valve actuation means 560 controllably displaces the exhaust valve sealing face 370 of each exhaust valve 358 away from its respective exhaust valve sealing surface 352 during each revolution of the crankshafts 52 and

54 and at a preselected range of movement of the low pressure piston assembly 56 in the operating chamber 22. The exhaust valves 358 are maintained against their respective exhaust valve seating surface 352 by the bias of exhaust valve springs 386 and the pressure of compression of air, combustion and expansion of exhaust gas in the combustion space 254. During reciprocal movement of the low pressure piston assembly 56 in the first direction, hydraulic fluid is pumped from the outer exhaust valve pump chambers 382 by the exhaust valve pistons 380 and transferred to the exhaust valve transfer pump chamber 568 by the exhaust valve transfer conduit 570. During reciprocal movement of the low pressure piston assembly 56 in the second direction, hydraulic fluid is pumped from the exhaust valve transfer pump chamber 568 by the transfer pump piston 566, which is attached to the low pressure piston by control member 464, and transferred to the outer exhaust valve pump chambers 382. Since the cross-sectional area of the exhaust valve transfer pump chamber 568 is equal to the combined cross-section areas of the exhaust valve pump chambers 378 associated with each of the exhaust valves 358 the result is merely the exchange of hydraulic fluid between the exhaust valve transfer pump chamber 568 and exhaust valve pump chambers 378.

The exhaust valves 358 are timed, as shown in FIG. 9, to be displaced from their respective exhaust valve seating surfaces 352 at the beginning of step H for a duration of approximately 90 degrees of crankshafts 52 and 54 rotation. During this interval, hydraulic fluid is pumped from the exhaust valve fluid actuator chamber 582 by the exhaust valve actuator piston 580 of the exhaust valve actuator cylinder assembly 574, to the outer exhaust valve pump chambers 382 by way of the branch conduit 592 and the exhaust valve transfer conduit 570. The exhaust valve actuator piston 580 is displaced by the exhaust valve cam follower 582 which rides on the exhaust valve actuator cam 588 driven by the engine 8. The exhaust valve actuator cam 588 makes one revolution for each revolution of the crankshafts 52 and 54. The additional volume of hydraulic fluid contributed by the action of the exhaust valve actuator piston 580 increases the volume of hydraulic fluid in the outer exhaust valve pump chambers 382 and acts on the ends of exhaust valve pump pistons 380, overcoming the bias of the exhaust valve springs 386 and the pressure from the expanding exhaust gas in the combustion chamber 254 acting on the ends of the exhaust valve head portions 368 within the combustion chamber, displacing the exhaust valves 358 from their respective seating surfaces 352. The additional volume of hydraulic fluid from the exhaust valve fluid actuator chamber 582 is forced to be transmitted to the outer exhaust valve pump chambers 382 since, the volume of the exhaust valve transfer pump chamber 568 cannot be increased. At this time, the volume of the exhaust valve transfer pump chamber 568 is being controllably reduced and the volume of the outer exhaust valve pump chambers 382 can be increased merely by displacing the exhaust valves 358 from their respective exhaust valve seating surfaces 352. This is accomplished by overcoming the bias of the exhaust valve springs 386 and the pressure from the expanding exhaust gas in the combustion chamber 254 acting on the ends of the exhaust valve head portions 368 within the combustion chamber 254.

The scavenge valve actuation means 594 controllably displaces the scavenge valve sealing face 438 of each scavenge valve 430 away from their respective scavenge valve seating surfaces 418 and 426 during each revolution of the crankshafts 52 and 54. The scavenge valves 430 are



maintained against their respective scavenge valve seating surfaces **418** and **426** by the bias of scavenge valve springs **454** and the pressure of the expansion of exhaust gas in the exhaust chamber **146**.

The scavenge valves **430** are timed, as shown in FIG. 9, to be displaced from their respective scavenge valve seating surfaces **418** and **426** at the beginning of step I for a duration of approximately 180 degrees of crankshafts **52** and **54** rotation. During this interval, hydraulic fluid is pumped from the scavenge valve fluid actuator chamber **604** by the scavenge valve actuator piston **602** of the scavenge valve actuator cylinder assembly **596**, to the outer scavenge valve pump chambers **450** by way of the conduit **614**. The scavenge valve actuator piston **602** is displaced by the scavenge valve cam follower **608** which rides on the scavenge valve cam **610** driven by the engine **8**. The scavenge valve cam **610** makes one revolution for each revolution of the crankshafts **52** and **54**. The additional volume of hydraulic fluid contributed by the action of the scavenge valve actuator piston **602** increases the volume and pressure of the hydraulic fluid in the outer scavenge valve pump chambers **450**. This increasing pressure acts on the ends of scavenge valve pump pistons **448**, overcoming the bias of the scavenge valve springs **454** and the pressure from the expanding exhaust gas in the exhaust chamber **146** acting on the ends of the scavenge valve head portions **436** within the exhaust chamber, displacing the scavenge valves **430** from their respective seating surfaces **418** and **426**.

The fuel introducing system **455** controllably injects fuel into the combustion space during each revolution of the crankshafts **52** and **54** and at approximately the beginning of step E as shown on FIG. 9. The fuel injector nozzle assembly **456** is mounted on the low pressure piston assembly **56** and communicates with the combustion space **254** as shown on FIGS. 7 and 8. The control member **464** is reciprocally positioned in the fuel pump cylinder **474** and connected for movement with the low pressure piston assembly **56**, controllably delivering fuel under high pressure from the fuel pump assembly **460** to the fuel injector nozzle assembly **456** in response to reciprocation of the low pressure piston assembly **56** in the first direction.

As shown on FIG. 8, the inner fuel pump chamber **498** is filled with fuel from the source **500** via the fuel line **502**, the transverse passage **504**, the fuel transfer passage **506**, the first port **510**, the fill passage **518**, and the second port **522** as the low pressure piston assembly **56** is moved in the second direction during step B as shown on FIG. 9.

As the low pressure piston assembly **56** is moved in the first direction during steps D and E, fuel is transferred from the inner fuel pump chamber **498** to the outer fuel pump chamber **494** by inward movement of the fuel pump piston portion **480** in the fuel pump cylinder **474**. The fuel is transferred by way of the fuel transfer passage **506**, the first fuel port **510**, the second fuel port **522**, the fill passage **518**, and the transverse passage **50**. Since the cross-sectional area of the fuel pump cylinder **474** in each of the inner fuel pump chamber **498** and outer fuel pump chamber **494** is the same and the cross-section area of the inner rod portion **482** and outer rod portion **476** the is the same, then the volume of fuel being transferred between the inner fuel pump chamber and the outer fuel pump chamber is equal.

During inward movement of the fuel pump piston portion **480** both transfer ports **510** and **522** are blocked by the cylindrical land surface **490** and the solenoid actuator valve **516** is energized, extending the blocking piston **514** into the fuel transfer passage **506** blocking the fuel transfer passage. For the period when both the transfer ports **510** and **522** and

the transfer passage **506** are blocked, fuel transfer from the inner fuel pump chamber **498** is prevented and fuel compression occurs until either the fuel injector nozzle assembly **456** opens or the solenoid actuated valve **516** is actuated to move the passage blocking piston **514** to its open position, unblocking the fuel transfer passage.

While the transfer ports **510** and **522** and the fuel transfer passage **506** are blocked the fuel is communicated under high pressure to the fuel injector nozzle assembly **456** by way of the axial fuel supply passage **548**. The high pressure fuel acts on the injector valve **540** within the injector valve bore **534**, overcoming the bias of the injector valve spring **538** moving the injector valve **540** away from the spray orifice means **536** and allowing the injection of fuel into the combustion chamber **254** through the spray orifice means in a conventional manner. To end injection, the solenoid valve **516** is actuated to move the passage blocking piston **514** out of the fuel transfer passage **506**, unblocking the fuel transfer passage reducing the pressure in the fuel pump chamber **498** and allowing the fuel to be transferred to the outer fuel pump chamber **494**.

The engine **8** is in complete balance with respect to forces and couples in the longitudinal, transverse, and perpendicular directions. This is achieved by having the rear first and third timing and balancing gears **74** and **96** in mesh with one another and the front second and fourth timing and balancing gears **80** and **100** in mesh with one another and having respective balance weights **78**, **82**, **98**, and **102** positioned approximately 180 degrees away from their respective adjacent crankpins **68** and **90**.

Separation of the combustion chamber **254** top surface **256**, bottom surface **258**, and concave side surfaces **260** and **262** from the housing **10** will reduced structure-born combustion noise.

The maximum volume of the exhaust chamber **146** exceeds that of the intake chamber **144**, this serves to reduce exhaust gas pressure and temperature when the scavenge valves **430** opens. In this manner efficiency is increased and noise is reduced relative to more conventional engines for which induction and exhaust volumes are equal.

In summary, it can be appreciated that compared to more conventional engines of equal power, the dual compression, dual expansion engine **8** is less than half the volume, is more efficient because it can use higher compression ratios with a more compact combustion chamber, and it has lower NO<sub>x</sub> emissions because it achieves high levels of exhaust retention without a loss of power.

Other aspects, objects, and advantages can be obtained from a study of the drawings, the disclosure and appended claims.

I claim:

1. A method of burning a mixture of combustible fuel and air in an engine (**8**) including a housing (**10**), piston means (**56**) reciprocally mounted in the housing (**10**) and partially defining an intake chamber (**144**) having a variable volume, an exhaust chamber (**146**) having a variable volume, and a combustion space (**254**) having a variable volume, a crankshaft (**52**) rotatably supported in the housing (**10**) and operatively connected to the piston means (**56**) for delivering power externally therefrom in response to combustion in the combustion space (**254**), the method having the steps comprising:

- i) moving the piston means (**56**) in the housing (**10**) increasing the volume of the intake chamber (**144**), inducting a charge of air into the intake chamber (**144**) and reducing the volume in the exhaust chamber (**146**), exhausting a charge of exhaust gas from the exhaust



chamber (146), with all these steps occurring during the same time interval;

ii) compressing another charge of air in the combustion space (254), introducing fuel into the combustion space (254) forming a combustible mixture with the another charge of air, igniting the combustible mixture, and forming a charge of expanding gas driving the piston means (56) transmitting the energy of expanding gas to the crankshaft (52), wherein these steps occur sequentially and during the time interval step W;

iii) moving the piston means (56) in the housing compressing the charge of air in the intake chamber (144), and transferring the charge of expanding gas to the exhaust chamber (146) which drives the piston means (56), thus transmitting energy to the crankshaft (52), with all these steps occurring during the same time interval subsequent to the time interval of steps i and ii; and

iiii) continuing to compress the charge of air in the intake chamber (144) while transferring the charge of compressed air into the combustion space (254) and expanding the charge of gas in the exhaust chamber (146), thus transmitting energy to the crankshaft (52), with all these steps occurring during the same time interval and subsequent to the time interval of step iii.

2. The method of claim 1 wherein the steps i, ii, iii, and iiii are completed in approximately 360 degrees of crankshaft (52) rotation.

3. The method of claim 1 wherein the steps i and ii are completed in approximately 180 degrees of crankshaft (52) rotation.

4. The method of claim 1 wherein the step iii is completed in approximately 90 degrees of crankshaft (52) rotation.

5. The method of claim 1 wherein the step iiii is completed in approximately 90 degrees of crankshaft (52) rotation.

6. An internal combustion engine (8) comprising:

a housing (10) defining an operating chamber (22) and having an induction passage (282-286) and a scavenge passage (414-422);

a multi-piston subassembly (50) including a first crankshaft (52) rotatably supported in the housing (10), a first piston assembly (56) including a body (110) defining a first bore (178) having a central axis (182) and an end surface (180), a second piston assembly (58) reciprocally disposed in the first bore (178) and defining therewith a combustion space (254), and means (204) for operatively connecting the second piston assembly (58) to the first crankshaft (52), the first piston assembly (56) being reciprocally disposed in the operating chamber (22) and defining therewith an intake chamber (144) and an exhaust chamber (146);

flow control means (266) for selectively communicating the induction passage (282-286) with the intake chamber (144), the intake chamber (144) with the combustion space (254), the combustion space (254) with the exhaust chamber (146), and the exhaust chamber (146) with the scavenge passage (414-422)

wherein the flow control means (266) includes induction means (268) for selectively communicating the induction passage (282-286) with the intake chamber, the housing (10) includes an induction port (288) and the induction means (268) which comprises an induction valve assembly (294) is operatively disposed in the induction port (288),

and an exhaust valve support means (360) includes an

exhaust valve guide (376) mounted in an exhaust valve pump cylinder (378) defined in the housing (10) and an exhaust valve piston (380) mounted on an end of the exhaust valve stem (366) of the exhaust valve (358) opposite an exhaust valve head portion (368), the exhaust valve guide (376) encompasses the exhaust valve stem (366), and the exhaust valve piston (380) is adapted for reciprocal sliding movement in the exhaust valve pump cylinder (378).

7. The internal combustion engine (8) of claim 6 wherein the housing (10) includes a plurality of identical operating chambers (22) transversely orientated with respect to the first crankshaft (52) and longitudinally spaced therealong.

8. The internal combustion engine (8) of claim 6 wherein the housing (10) includes a first housing portion (12) and a second housing portion (14) removably secured together.

9. The internal combustion engine (8) of claim 8 wherein the first housing portion (12) defines a first open generally oblong cavity (18) having a preselected width, length, and height and the second housing portion (14) defines an second open generally oblong cavity (20) having a preselected width, length and height.

10. The internal combustion engine (8) of claim 9 wherein the first cavity (18) is defined by a pair of generally parallel side surfaces (24-26), a pair of generally semicylindrical end surfaces (28-30) that blendingly connect together the side surfaces (24-26), and a ceiling surface (32), and the second cavity (20) is defined by a pair of generally parallel side surfaces (40-42), a pair of generally semicylindrical end surfaces (44-46) and a bottom surface (48).

11. The internal combustion engine (8) of claim 10 wherein the first and second cavities (18-20) are arranged in an opposed and aligned relationship to form the operating chamber (22).

12. The internal combustion engine (8) of claim 6 wherein the first crankshaft (52) includes a plurality of longitudinally aligned main bearing journals (62) having a central axis (66) disposed generally at a right angle to the side surfaces (24-26-40-42) of the cavities (18-20) and a crankpin (68).

13. The internal combustion engine (8) of claim 6 wherein the body (110) of the first piston assembly (56) is of generally oblong shape having a pair of generally parallel side surfaces (112-114) a first end portion (116), a second end portion (118), a top working surface (140), and a bottom working surface (142).

14. The internal combustion engine (8) of claim 6 wherein the housing (10) defines a plurality of induction ports (288) and the induction means (268) includes a plurality of induction valve assemblies (294) one of which is operatively disposed in each of the induction ports (288).

15. The internal combustion engine (8) of claim 6 wherein the flow control means (266) includes intake valve means (270) selectively communicating the intake chamber (144) with the combustion space (254).

16. The internal combustion engine (8) of claim 15 wherein the intake valve means (270) includes an intake valve assembly (316).

17. The internal combustion engine (8) of claim 6 wherein the flow control means (266) includes exhaust valve means (272) for selectively communicating the combustion space (254) with the exhaust chamber (146).

18. The internal combustion engine (8) of claim 17 wherein the exhaust valve means (272) includes a valve operating mechanism (356), the valve operating mechanism (356) includes an exhaust valve (358), exhaust valve support means (360) for reciprocally supporting the exhaust valve (358) on the housing (10) for movement with the first piston



assembly (56), and exhaust valve actuating means (560) for actuating the exhaust valve (358).

19. The internal combustion engine (8) of claim 10 wherein an outer exhaust valve pump chamber (382) is defined in the exhaust valve pump cylinder (378) outwardly of the exhaust valve piston (380), an inner exhaust valve spring chamber (384) is defined in the exhaust valve pump cylinder (378) inwardly of the exhaust valve piston (380) and an exhaust valve spring (386) is disposed in the exhaust valve spring chamber (384) and extends between the exhaust valve guide (376) and the exhaust valve piston (380) to urge the exhaust valve sealing face (370) of the exhaust valve (358) against the exhaust valve seating surface (352) until the head portion (368) is moved away from the exhaust valve seating surface (252).

20. The internal combustion engine (8) of claim 19 wherein the exhaust valve actuating means (560) includes transfer means (562) for transferring fluid between the transfer means (562) and the outer exhaust valve pump chamber (382), the transfer means (562) includes a transfer pump cylinder (564) defined in a pump body (462) removably secured to the housing (10), a control member (464) connected for movement with the first piston assembly (56), and an exhaust valve actuator cylinder assembly (574), the control member (464) includes a rod portion (478) that extends into the transfer pump cylinder (564), a transfer piston (566) mounted on an end of the rod portion (478) for reciprocal movement therewith, a transfer pump chamber (568) is defined in the transfer pump cylinder (564) between the transfer piston (566) and one end of the transfer pump chamber (564) with the cross-sectional area of the transfer pump chamber (564) being equal to the cross-sectional area of the outer exhaust valve pump chamber (382), and a transfer conduit (570) interconnecting the transfer pump chamber (564) with the outer exhaust valve pump chamber (382).

21. The internal combustion engine (8) of claim 20 wherein the exhaust valve actuator cylinder assembly (574) includes an exhaust valve actuator body (576) defining an exhaust valve actuator piston bore (578) with an exhaust valve actuator piston (580) slidably disposed in the exhaust valve actuator bore (578), an exhaust valve actuator fluid actuator chamber (582) having a preselected volume defined in the exhaust valve actuator piston bore (578) between the exhaust valve actuator piston (580) and one end of the exhaust valve actuator chamber (582), an exhaust valve piston rod (584) connected to the exhaust valve actuator piston (580) opposite the exhaust valve actuator chamber (582), an exhaust valve cam follower (586) connected to an end of the exhaust valve rod (584) and riding on an exhaust valve cam (588) driven by the engine (8), and an exhaust valve actuator spring (590) disposed in the exhaust valve actuator chamber (582) between the exhaust valve actuator piston (580) and the end of the exhaust valve actuator chamber (582) biasing the exhaust valve cam follower (586) against the exhaust valve cam (588), the exhaust valve actuator piston (580) operative in response to movement of the exhaust valve cam follower (586) to displace fluid from the exhaust valve actuator chamber (582) to the outer exhaust valve pump chamber (382) for controllably displacing the exhaust valve sealing face (370) of the exhaust valve (358) away from the exhaust valve seating surface (352) at a preselected time.

22. The internal combustion engine (8) of claim 21 wherein the exhaust valve cam (588) makes one revolution for each revolution of the crankshaft (52).

23. The internal combustion engine (8) of claim 21

wherein the body (110) of the first piston assembly (56) defines a second exhaust port (346) having a central axis (350), the second exhaust port (346) extends between the bottom surface (258) of the combustion space (254) and the bottom working surface (142) of the body (110) of the first piston assembly (56), and another exhaust valve (358) is operatively disposed in the second exhaust port (346).

24. The internal combustion engine (8) of claim 6 wherein the flow control means (266) includes scavenge means (274) for selectively communicating the exhaust chamber (146) with the scavenge passage (414-422).

25. The internal combustion engine (8) of claim 24 wherein the scavenge means (274) includes a scavenge operating mechanism (428), the scavenge operating mechanism (428) includes a scavenge valve (430), scavenge valve support means (432) for reciprocally supporting the scavenge valve (430) on the housing (10), and scavenge valve actuating means (594) for actuating the scavenge valve (430).

26. The internal combustion engine (8) of claim 25 wherein the housing (10) defines a scavenge port (410) and the scavenge valve (430) is operatively disposed in the scavenge port (410).

27. The internal combustion engine (8) of claim 13 wherein the engine (8) includes a fuel introducing system (456) the fuel introducing system (456) includes a fuel injector nozzle assembly (456) mounted on the first piston assembly (56) and communicating with the combustion space (254) and fuel injection means (458) connected for movement with the first piston assembly (56) for controllably delivering fuel under pressure to the fuel injector nozzle assembly (456) in response to reciprocation of the first piston assembly (56).

28. The internal combustion engine (8) of claim 27 wherein a nozzle bore (526) having a central axis (470) is defined in the body (110) of the first piston assembly (56) extending from the top working surface (140) and opening into the combustion space (254), and the fuel injector nozzle assembly (456) is operatively disposed in the nozzle bore (526) to selectively inject fuel into the combustion space (254).

29. The internal combustion engine (8) of claim 10 wherein the multi-piston subassembly (50) includes a second crankshaft (54) rotatably supported in the housing (10) and includes a plurality of longitudinally aligned main bearing journals (84) having a central axis (88) disposed at a right angle to the side surfaces (24-26-40-42) of the cavities (18-20), and a crankpin (90).

30. The internal combustion engine (8) of claim 29 wherein a second crankshaft clearance passage (162) is defined in the body (110) of the first piston assembly (56) adjacent the second end portion (118), the second clearance passage (162) is arranged generally perpendicular to the side surfaces (112-114) and approximately midway between the top and bottom working surfaces (140-142), the second crankshaft (54) being operatively disposed in the second clearance passage (162) without making contact therewith.

31. The internal combustion engine (8) of claim 30 wherein the body (110) defines a second piston bore (186) having an end surface (188), the second piston bore (186) has a central axis (190) and extends inward from the first semicylindrical end surface (130) of the second end portion (118) with the central axis (190) of the second piston bore (186) being coaxial with the central axis (182) of the first piston bore (178).

32. The internal combustion engine (8) of claim 31 wherein the multi-piston subassembly (50) includes a third



piston assembly (60) reciprocally disposed in the second piston bore (186) and means (204) for connecting the third piston assembly (60) to the second crankshaft (54).

33. The internal combustion engine (8) of claim 32 wherein the third piston assembly (60) includes a body portion (198) and means (204) for connecting the third piston assembly (60) to the second crankshaft (54), the body portion (198) includes a generally cylindrical head end (208) having a working surface (210) facing the end surface (180) of the second piston bore (178) and a coupling end (212) defining a semicylindrical surface (220).

34. The internal combustion engine (8) of claim 33 wherein the third piston assembly (60) is connected directly to the second crankshaft (54) and the means (204) for connecting the third piston assembly (58) directly to the second crankshaft (54) includes a bearing cap (200) defining a semicylindrical surface (222), a pair of bearing shells (202-204) disposed in the semicylindrical surface (220) of the coupling end (212) and the semicylindrical surface (222), and a plurality of fasteners (206) to removably secure the bearing cap (200) to the coupling end (212).

35. The internal combustion engine (8) of claim 33 wherein the head end (208) of the body portion (198) defines a plurality of sealing ring grooves (216) which are adapted to receive a plurality of sealing rings (218) for sealing engagement with the second piston bore (186).

36. The internal combustion engine (8) of claim 35 wherein the working surfaces (210) of the second and third piston assemblies (50-60) oppose each other and the combustion space (254) is disposed between the working surfaces (210).

37. The internal combustion engine (8) of claim 29 wherein a first timing and balancing gear (74) having a balance weight (78) positioned approximately 180 degrees away from the adjacent crankpin (68) is connected to a rear power take-off end (76) of the first crankshaft (52) and a third timing and balance gear (96) having a balance weight (98) positioned approximately 180 degrees away from the adjacent crankpin (90) is connected to a rear end (97) of the second crankshaft (54), the first and third timing and balancing gears (74-96) are in mesh with one another imparting phased counter rotation of the first and second crankshafts (52-54).

38. The internal combustion engine (8) of claim 37 wherein a second timing and balancing gear (80) having a balance weight (82) positioned approximately 180 degrees away from the adjacent crankpin (68) is connected to a front end (81) of the first crankshaft (52) and a fourth timing and balance gear (100) having a balance weight (102) positioned approximately 180 degrees away from the adjacent crankpin (90) is connected to a front end (101) of the second crankshaft (54), the second and fourth timing and balancing gears (80-100) are in mesh with one another imparting phased counter rotation of the first and second crankshafts (52-54).

39. The internal combustion engine (8) of claim 38 wherein the housing (10) defines a plurality of the operating chambers (22) with one of a plurality of the multi-piston subassemblies (50) being reciprocally disposed in each of the operating chambers (22) and each operating chamber (22) includes the flow control means (266) and the fuel introducing system (456) operatively associated therewith.

40. An internal combustion engine (8) comprising:
- a housing (10) defining an operating chamber (22) and having an induction passage (282-286) and a scavenge passage (414-422);
  - a first multi-piston subassembly (50) reciprocally mounted in the operating chamber (22) and defining

therewith an intake chamber (144) and an exhaust chamber (146), the first multi-piston subassembly (50) including a body (110) defining a first and second coaxial aligned bore (178-186), a second and third piston assembly (58-56) reciprocally disposed in an opposed relationship in the first and second bores (178-186) and defining with the body (110) a combustion space (254) therebetween, a first and second crankshaft (52-54) respectively connected directly to the second and third piston assemblies (58-56) for delivering power externally therefrom in response to combustion in the combustion space (254).

41. The internal combustion engine (8) of claim 40 wherein the housing (10) includes a plurality of identical, transversely orientated and longitudinally spaced operating chambers (22).

42. The internal combustion engine (8) of claim 41 wherein the housing (10) includes a first housing portion (12) and a second housing portion (14) removably secured together.

43. The internal combustion engine (8) of claim 42 wherein the first housing portion (12) defines a first open generally oblong cavity (18) having a preselected width, length, and height and the second housing portion (14) defines a second open generally oblong cavity (20) having a preselected width, length and height.

44. The internal combustion engine (8) of claim 43 wherein the first cavity (18) is defined by a pair of generally parallel side surfaces (24-26), a pair of generally semicylindrical end surfaces (28-30) that blendingly connect together the side surfaces (24-26), and a ceiling surface (32), and the second cavity (20) is defined by a pair of generally parallel side surfaces (40-42), a pair of generally semicylindrical end surfaces (44-46) and a bottom surface (48).

45. The internal combustion engine (8) of claim 44 wherein the first and second cavities (18-20) are arranged in an opposed and aligned relationship to form the operating chamber (22).

46. The internal combustion engine (8) of claim 45 wherein the width of the second cavity (20) is the same as the width of the first cavity (18).

47. The internal combustion engine (8) of claim 46 wherein length of the second cavity (20) is greater than the length of the first cavity (18).

48. The internal combustion engine (8) of claim 47 wherein height of the first and second cavities (18-20) are the same.

49. The internal combustion engine (8) of claim 40 wherein the first crankshaft (52) includes a plurality of longitudinally aligned main bearing journals (62) having a central axis (66) disposed generally at a right angle to the side surfaces (24-26-40-42) of the cavities (18-20) and a crankpin (68) and the second crankshaft (54) includes a plurality of longitudinally aligned main bearing journals (84) having a central axis (88) and a crankpin (90), the central axes (66-88) of the bearing journals (62-84) of the first and second crankshafts (52-54) being parallel.

50. The internal combustion engine (8) of claim 49 wherein a first timing and balancing gear (74) having a balance weight (78) positioned approximately 180 degrees away from the adjacent crankpin (68) is connected to a rear end (76) of the first crankshaft (52) and a third timing and balance gear (96) having a balance weight (98) positioned approximately 180 degrees away from the adjacent crankpin (90) is connected to a rear end (97) of the second crankshaft (54), the first and third timing and balancing gears (74-96)



are in mesh with one another imparting phased counter rotation of the first and second crankshafts (52-54).

51. The internal combustion engine (8) of claim 50 wherein a second timing and balancing gear (80) having a balance weight (82) positioned approximately 180 degrees away from the adjacent crankpin (68) is connected to a front end (81) of the first crankshaft (52) and a fourth timing and balance gear (100) having a balance weight (102) positioned approximately 180 degrees away from the adjacent crankpin (90) is connected to a rear end (101) of the second crankshaft (54), the second and fourth timing and balancing gears (80-100) are in mesh with one another imparting phased counter rotation of the first and second crankshafts (52-54).

52. The internal combustion engine (8) of claim 40 wherein the body (110) of the first piston assembly (56) is of generally oblong shape having a pair of generally parallel side surfaces (112-114) a first end portion (116), a second portion (118), a top working surface (140), and a bottom working surface (142).

53. The internal combustion engine (8) of claim 52 wherein the top and bottom working surfaces (140-142) of the body (110) of the first piston assembly (56) are generally parallel to each other and generally perpendicular to the side surfaces (112-114) thereof.

54. The internal combustion engine (8) of claim 53 wherein the first end portion (116) of the body (110) includes a first semicylindrical end surface (120) and the second end portion (118) includes a first semicylindrical end surface (130).

55. The internal combustion engine (8) of claim 54 wherein a band (148) extends fully around the periphery of the side surfaces (112-114) and the first semicylindrical end surfaces (120-130) of the first and second end portions (116-118) adjacent the top working surface (140), the band (148) defines a plurality of ring grooves (150) and a plurality of sealing rings (152) are received in the ring grooves (150).

56. The internal combustion engine (8) of claim 55 wherein the first end portion (116) includes a second semicylindrical end surface (122) that extends outwardly beyond the first semicylindrical end surface (120) to form a flange portion (126) and the second end portion (118) includes a second semicylindrical end portion (132) that extend outwardly beyond the first semicylindrical end surface (130) of the second end portion (118) to form a flange portion (134).

57. The internal combustion engine (8) of claim 56 wherein a band (154) extends fully around the periphery of the side surfaces (112-114) and the second semicylindrical end surfaces (122-132) of the first and second end portions (116-118) adjacent the bottom working surface (142), the band (154) defines a plurality of ring grooves (156) and a plurality of sealing rings (158) are received in the ring grooves (156).

58. The internal combustion engine (8) of claim 57 wherein a first crankshaft clearance passage (160) is defined in the body (110) adjacent the first end portion (116), the first clearance passage (160) is arranged generally perpendicular to the side surfaces (112-114) and approximately midway between the top and bottom working surfaces (140-142), and the first crankshaft (52) is operatively disposed in the first clearance passage (160) without making contact therewith.

59. The internal combustion engine (8) of claim 58 wherein a second crankshaft clearance passage (162) is defined in the body (110) of the first piston assembly (56) adjacent the second end portion (118), the second clearance passage (162) is arranged generally perpendicular to the side surfaces (112-114) and approximately midway between the

top and bottom working surfaces (140-142), and the second crankshaft (54) is operatively disposed in the second clearance passage (162) without making contact therewith.

60. The internal combustion engine (8) of claim 30 wherein the first piston bore (178) having an end surface (180) extends inwardly from the first semicylindrical end surface (120) of the first end portion (116) with the central axis (182) being located on a first plane that is substantially parallel to and midway between the side surfaces (112-114) of the body (110) and on a second plane that is substantially parallel to and midway between the top and bottom working surfaces (140-142).

61. The internal combustion engine (8) of claim 60 wherein the second piston bore (186) includes a central axis (190) and an end surface (188), the second piston bore (186) extends inwardly from the first semicylindrical end surface (130) of the second end portion (118).

62. The internal combustion engine (8) of claim 61 wherein the second and third piston assemblies (56-58) are identical and each include a body portion (198) and means (224) for connecting the respective second and third piston assemblies (56-58), directly to the first and second crankshafts (52-54).

63. The internal combustion engine (8) of claim 60 wherein the body portion (198) includes a generally cylindrical head end (208) having a working surface (210) facing the respective end surfaces (180-188) of the first and second piston bores (178-146) and a coupling end (212) defining a semicylindrical surface (220), the means (204) for connecting the respective second and third piston assemblies (56-58) directly to the first and second crankshafts (52-54) includes the coupling end (212), a bearing cap (200) defining a semicylindrical surface (222), a pair of bearing shells (202-204) disposed in the semicylindrical surfaces (220-222) of the coupling end (212) and the bearing cap (200), and a plurality of fasteners (206) to removably secure the bearing cap (200) to the coupling end (212).

64. The internal combustion engine (8) of claim 63 wherein the head end (208) of each of the second and third piston assemblies (56-58) defines a plurality of sealing ring grooves (216) which are adapted to receive a plurality of sealing rings (218) for sealing engagement with the respective first and second piston bores (178-186).

65. The internal combustion engine (8) of claim 40 including flow control means (266) for selectively communicating the induction passage (282-286) with the intake chamber (144), the intake chamber (144) with the combustion space (254), the combustion space (254) with the exhaust chamber (146), and the exhaust chamber (146) with the scavenge passage (414-422).

66. The internal combustion engine (8) of claim 65 wherein the flow control means (266) includes induction means (268) for selectively communicating the induction passage (282-286) with the intake chamber (144).

67. The internal combustion engine (8) of claim 66 wherein the housing (10) defines an induction port (288) and the induction means (268) includes an induction valve assembly (294) operatively disposed in the induction port (288).

68. The internal combustion engine (8) of claim 67 wherein an induction valve seating surface (290) is defined in the ceiling surface (32) of the housing (10) about the induction port (288), and the induction valve assembly (294) includes an induction valve (296) having an induction valve stem (300) and an induction valve head portion (302) disposed at an end of the induction valve stem (300), the induction valve head portion (302) defining an induction



valve sealing face (304) and being of a dimension sufficient for sealingly seating of the induction valve sealing face (304) on the induction valve seating surface (290).

69. The internal combustion engine (8) of claim 68 wherein the induction valve assembly (294) includes an induction valve spring (298) for urging the induction valve (296) against the induction valve seating surface (290).

70. The internal combustion engine (8) of claim 67 wherein the housing (10) defines a plurality of induction ports (288) and another induction valve assembly (294) is operatively disposed in each of the induction ports (288).

71. The internal combustion engine (8) of claim 70 wherein another induction valve seating surface (290) is defined in the ceiling surface (32) of the housing (10) about each of the induction ports (288), and the another induction valve assembly (294) includes another induction valve (296) having another induction valve stem (300) and another induction valve head portion (302) disposed at an end of the another induction valve stem (300), the another induction valve head portion (302) defining another induction valve sealing face (304) and being of a dimension sufficient for sealingly seating of the another induction valve sealing face (304) on the another induction valve seating surface (290).

72. The internal combustion engine (8) of claim 71 wherein the another induction valve assembly (294) includes another induction valve spring (298) for urging the another induction valve (296) against the another induction valve seating surface (290).

73. The internal combustion engine (8) of claim 65 wherein the flow control means (266) includes intake means (270) for selectively communicating the intake chamber (144) with the combustion space (254).

74. The internal combustion engine (8) of claim 73 wherein the intake valve means (270) includes an intake valve assembly (316).

75. The internal combustion engine (8) of claim 74 wherein the body (110) of the first piston assembly (56) defines a first intake port (306) having a central axis (310), the first intake port (306) extends between the top working surface (140) and a top surface (256) of the combustion space (254) and the intake valve assembly (316) is operatively disposed in the first intake port (306).

76. The internal combustion engine (8) of claim 75 wherein an intake valve seating surface (314) is defined in the top surface (256) about the first intake port (306), the intake valve assembly (316) includes an intake valve (320) having an intake valve stem (324), an intake valve head portion (326) disposed at the end of the intake valve stem (324), the intake valve head portion (326) defines an intake valve sealing face (328) and an intake valve spring (322) disposed between the body (110) and the end of the intake valve stem (324) for urging the intake valve sealing face (328) against the intake valve seating surface (314).

77. The internal combustion engine (8) of claim 76 wherein the body (110) defines a second intake port (308) having a central axis (312), the second intake port (308) extends between the top working surface (140) and top surface (256) of the combustion space (254) and the intake valve assembly (316) is operatively disposed in the second intake port (308).

78. The internal combustion engine (8) of claim 77 wherein another intake valve seating surface (314) is defined in the top surface (256) about the second port (308), and the another intake valve assembly (316) includes another intake valve (320) having another intake valve stem (324) and another intake valve head portion disposed at an end of the another intake valve stem (324) defining another intake

valve sealing face (328), and another intake valve spring (322) disposed between the body (110) and the end of the another intake valve stem (324) for urging the another intake valve sealing face (328) against the another intake valve seating surface (314).

79. The internal combustion engine (8) of claim 78 wherein the central axes (310-312) of the first and second intake ports (306-308) are generally longitudinally aligned between the side surfaces (112-114) of the body (110) and approximately midway between the end surfaces (120-130) thereof.

80. The internal combustion engine (8) of claim 65 wherein the flow control means (226) includes exhaust means (272) for selectively communicating the combustion space (254) with the exhaust chamber (146).

81. The internal combustion engine (8) of claim 80 wherein the exhaust means (272) includes an valve operating mechanism (356), the first valve operating mechanism (356) includes an exhaust valve (358), exhaust valve support means (360) for reciprocally supporting the exhaust valve (358) on the housing (10) and for movement with the first piston assembly (56), and exhaust valve actuating means (560) for actuating the exhaust valve (358).

82. The internal combustion engine (8) of claim 81 wherein the body (110) of the first piston (56) defines an exhaust port (344) having a central axis (348), the first exhaust port (344) extending between the bottom working surface (142) and a bottom surface (258) of the combustion space (254) and the exhaust valve (358) is operatively disposed in the first exhaust port (344).

83. The internal combustion engine (8) of claim 82 wherein an exhaust valve seating surface (352) is defined in the bottom surface (258) about the first exhaust port (344), the exhaust valve (358) includes an exhaust valve stem (366) and an exhaust valve head portion (368) defining an exhaust valve sealing face (370) and being of a dimension sufficient for sealingly seating of the exhaust valve sealing face (370) on the exhaust valve seating surface (352).

84. The internal combustion engine (8) of claim 83 wherein the exhaust valve support means (360) includes an exhaust valve guide (376) mounted in an exhaust valve pump cylinder (378) defined in the bottom surface (48) of the housing (10) and an exhaust valve piston (380) is mounted on an end of the exhaust valve stem (366) opposite the exhaust valve head portion (368), the exhaust valve guide (376) encompasses the exhaust valve stem (366) and the exhaust valve piston (380) is adapted for reciprocal sliding movement in the exhaust valve pump cylinder (378).

85. The internal combustion engine (8) of claim 84 wherein an exhaust valve pump chamber (382) is defined in the exhaust valve pump cylinder (378) outwardly of the exhaust valve piston (380), an exhaust valve spring chamber (384) is defined in the exhaust valve pump cylinder (378) inwardly of the exhaust valve piston (380) and an exhaust valve spring (386) is disposed in the exhaust valve spring chamber (384) and extends between the exhaust valve guide (376) and the exhaust valve piston (380) to urge the exhaust valve sealing face (370) of the exhaust valve (358) against the exhaust valve seating surface (352) until the exhaust valve head portion (368) is moved away from the exhaust valve seating surface (252).

86. The internal combustion engine (8) of claim 85 wherein the exhaust valve actuating means (560) includes transfer means (562) for transferring fluid between the transfer means (562) and the exhaust valve pump chamber (382), the transfer means (562) includes a transfer pump cylinder (564) defined in a pump body (462) removably



secured to the housing (10), a control member (464) connected for movement with the first piston assembly (56), and an exhaust valve actuator assembly (574), the control member (464) includes a rod portion (478) that extends into the transfer pump cylinder (564), a transfer pump piston (566) is mounted on an end of the rod portion (478) for reciprocal movement therewith, a transfer pump chamber (564) is defined in the transfer pump cylinder (564) between the transfer pump piston (566) and one end of the transfer pump chamber (564) with the cross-sectional area of the transfer pump chamber (564) being equal to the cross-sectional area of the exhaust valve pump chamber (382), a transfer conduit (570) interconnects the transfer pump chamber (564) with the exhaust valve pump chamber (382).

87. The internal combustion engine (8) of claim 86 wherein the exhaust valve actuator cylinder assembly (574) includes an exhaust valve actuator body (576) defining an exhaust valve actuator piston bore (578) with an exhaust valve actuator piston (580) slidably disposed in the exhaust valve actuator bore (578), an exhaust valve actuator fluid actuator chamber (582) having a preselected volume defined in the exhaust valve actuator piston bore (578) between the exhaust valve actuator piston (580) and one end of the exhaust valve actuator chamber (582), an exhaust valve piston rod (584) connected to the exhaust valve actuator piston (580) opposite the exhaust valve actuator chamber (582), an exhaust valve cam follower (586) connected to an end of the exhaust valve rod (584) and riding on an exhaust valve cam (588) driven by the engine (8), and an exhaust valve actuator spring (590) disposed in the exhaust valve actuator chamber (582) between the exhaust valve actuator piston (580) and the end of the exhaust valve actuator chamber (582) biasing the exhaust valve cam follower (586) against the exhaust valve cam (588), the exhaust valve actuator piston (580) operative in response to movement of the exhaust valve cam follower (586) to displace fluid from the exhaust valve actuator chamber (582) to the exhaust valve pump chamber (382) for controllably displacing the exhaust valve sealing face (370) of the exhaust valve (358) away from the exhaust valve seating surface (352) at a preselected time.

88. The internal combustion engine (8) of claim 87 wherein the exhaust valve cam (588) makes one revolution for each revolution of the crankshaft (52).

89. The internal combustion engine (8) of claim 65 wherein the flow control means (266) includes scavenge means (274) for selectively communicating the exhaust chamber (146) with the scavenge passage (414-422).

90. The internal combustion engine (8) of claim 89 wherein the scavenge means (274) includes a scavenge operating mechanism (428), the scavenge operating mechanism (428) includes a scavenge valve (430), scavenge valve support means (432) for reciprocally supporting the scavenge valve (430) on the housing (10), and scavenge valve actuating means (594) for actuating the scavenge valve (430).

91. The internal combustion engine (8) of claim 90 wherein the housing (110) defines a scavenge port (410) and the scavenge valve (430) is operatively disposed in the scavenge port (410).

92. The internal combustion engine (8) of claim 52 including a fuel introducing system (455), the fuel introducing system (455) including fuel injection means (458) for injecting a combustible fuel into the combustion space (254).

93. The internal combustion engine (8) of claim 92 wherein the fuel introducing system (455) includes a fuel

injector nozzle assembly (456) mounted on the first piston assembly (56) and communicating with the combustion space (254) and the fuel injection means (458) is connected for movement with the first piston assembly (56) for controllably delivering fuel under pressure to the fuel injector nozzle assembly (456) in response to reciprocation of the first piston assembly (56).

94. The internal combustion engine (8) of claim 93 wherein a nozzle bore (526) having a central axis (470) is defined in the body (110) of the first piston assembly (56) extending from the top working surface (140) and opening into the combustion space (254), and the fuel injector nozzle assembly (456) is operatively disposed in the nozzle bore (526) to selectively inject fuel into the combustion space (254).

95. The internal combustion engine (8) of claim 94 wherein the fuel injector nozzle assembly (456) includes an injector body (530) defining a flow charge passage (532), an injector valve bore (534), an injector valve (540) reciprocally disposed in the injector valve bore (534) and biased by a spring (538), and spray orifices means (536) in fluid communication with injector valve bore (534) and the combustion space (254).

96. The internal combustion engine (8) of claim 95 wherein the fuel injection means (458) includes a fuel pump assembly (460), the fuel pump assembly (460) includes a pump body (462) and communication means (463), a fuel pump cylinder (474) having a central axis (475) defined in the pump body (462) and the communication means (463) is reciprocally disposed in the fuel pump cylinder (474).

97. The internal combustion engine (8) of claim 96 wherein the upper portion (12) of the housing (10) defines a mounting bore (468) having a central axis (470) and the pump body (462) is removably secured therein, the central axis (470) is located on a first plane that is substantially parallel to and midway between the side surfaces (24-26) of the operating chamber (22) and on a second plane disposed substantially perpendicular to the side surfaces (24-26) and substantially midway between the semicylindrical end surfaces (28-44) of the operating chamber (22).

98. The internal combustion engine (8) of claim 97 wherein the central axis (470) of the mounting bore (468) and the central axis (475) of the fuel pump cylinder (474) are coaxial.

99. The internal combustion engine (8) of claim 98 wherein communication means (463) includes a control member (464), the control member (464) includes an outer rod portion (476) that extends through an outer rod bore (478) defined in the pump body (462), an intermediate fuel pump piston portion (480), and an inner rod portion (482) that extends through an inner rod bore (484) defined in the pump body (462), the cross-sectional areas of the inner and outer rod portions (476-482) within the fuel pump cylinder (474) are identical, the intermediate fuel pump piston portion (480) includes an outer control end surface (488), a cylindrical land surface (490) of a predetermined axial length, and an inner control end surface (492), an outer fuel pump chamber (494) is defined in the fuel pump cylinder (474) outwardly of the intermediate fuel pump piston portion (480) and an inner fuel pump chamber (498) is defined in the fuel pump cylinder (474) inwardly of the intermediate fuel pump piston portion (480).

100. The internal combustion engine (8) of claim 99 wherein the outer fuel pump chamber (494) is supplied fuel from a source (500) via a fuel passage (502) and a transverse passage (504) defined in the pump body (462), a fuel transfer passage (506) is defined in the pump body (462) intercon-



necting the outer and inner fuel pump chambers (494-498), a first fuel pump port (510) defined in the pump body (462) connects the transfer passage (506) to the fuel pump cylinder (474), a passage blocking piston (514) of a solenoid actuated valve (516) is located in the transfer passage (506) between the outer fuel pump chamber (494) and the connection of the first port (510) and is operative to selectively block fluid flow therethrough, a fill passage (518) is defined in the pump body (462) connecting the transverse passage (504) with the pump fuel cylinder (474), and a second fuel pump port (522) is defined in the pump body (462) spaced axially inwardly of the first fuel pump port (510) and connects the fuel pump cylinder (474) to the fill passage (518).

101. The internal combustion engine (8) of claim 100 wherein inner rod portion (482) of the control member (464) includes an enlarged end portion (544) threadably secured to

the first piston assembly (56), the end portion (544) includes a counterbore (546) that encompasses the injector body (530) of the injector nozzle assembly (456) capturing the injector nozzle assembly in the nozzle bore (526), the inner rod portion (482) further includes an axial supply passage (548) that connects the inner fuel pump chamber (498) of the fuel pump cylinder (474) to the flow charge passage (532) in the injector body (530).

102. The internal combustion engine (8) of claim 101 wherein the housing (10) defines a plurality of the operating chambers (22) with the multi-piston subassembly (50) being reciprocally disposed in each of the operating chambers (22) and each operating chamber (22) has the flow control means (266) and the fuel introducing system (455).

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